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Edited by L. H. Bailey

SOILS

THEIR PROPERTIES AND MANAGEMENT

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SOILS

THEIR PROPERTIES AND MANAGEMENT

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CHAPTER XXXI

SOILS: THEIR PROPERTIES AND MANAGEMENT

CHAPTER I

SOME GENERAL CONSIDERATIONS

The broken and weathered fragments of rock that cover in a thin layer the solid part of the earth and that furnish the foothold and, in part, the sustenance for plant life, are termed soil. Soil comes from rock and returns to rock. It is merely a transitory stage in the change from one form of rock to another. It is never still. From the time when the particle leaves the disintegrating rock until it is again cemented in the skeleton of the earth, it is subjected to almost constant movement and to the action of numerous forces that change it chemically and physically. It is the movement, the strain and the stress, the hard treatment at the hands of disintegrating agencies, that make the soil useful to plant life.

It was only the simpler forms of plants, however, that first throve on the pulverized rock. Tribe after tribe of plants has invaded the soil. Each has wrested from it the mineral matter necessary for its growth and development. Each has, in the end, left not only the mineral matter that it obtained from the disintegrated rock, but also the carbon and the oxygen that had been won from the

air in the struggle for life. Primitive plants have been followed by more highly organized ones as the incursions have gone on, and always to the profit of the soil, until the soil has accumulated a great store of organic matter and a teeming population of microscopic life.

This débris of rock and plant residue that has accumulated through the centuries of struggle is the arable soil from which man obtains his bread. The study of this soil is a history of strife and struggle, and as the light of investigation is turned on it, new contestants, new operations, new results, and new principles are brought to view and the story must be retold.

1. **Composition of the soil.** — Broadly speaking, the soil is composed of two general classes of materials, rock and organic matter. The former usually makes up the bulk of the soil, while the latter occurs under normal conditions in relatively small amounts. In spite of this low proportion, however, its presence is of vital importance to productivity. The soil has also three general phases — the physical, the chemical, and the biological. In the physical phase, the size and shape of particle, the movement of air and water, and other physical properties are dealt with; in the chemical phase, the composition of the particle, of the organic matter, and of the soil solution is of dominant importance; in the biological phase, the soil is seen to be not an inert material, but teeming with life — minute forms of life, to be sure, but of great importance in the manufacture of food for plants. Under these three general phases, then, the changes going on in a soil may be studied, and they are found to be directed primarily toward the production and maintenance of conditions favorable for plant growth. The soil is not a simple medium to study, but is extremely complicated

for two reasons: first, because of the complicated nature of its two general constituents; and secondly, because of the action and interaction of these constituents with each other.

2. Factors for plant growth. — The growth and development of a plant are largely the result of two sets of factors, the internal and the external. The former depends on the nature of the plant itself, the latter on its environment. The external factors of plant growth under normal conditions may be classified as follows: (1) mechanical support, (2) air, (3) heat, (4) light, (5) water, and (6) food. With the exception of light, the soil supplies, either wholly or in part, all the conditions named. As a mere mass of ground-up rock with which are mixed varying quantities of decayed organic matter, the soil acts as a medium for root development and thereby provides a foothold for the plant. Air, heat, and water are supplied as a consequence of the inherent physical condition of a soil. The circulation of water serves to bring food into solution for absorption by the rootlets. Thus the two prime functions of the soil are realized — the supplying of plant-food and of a foothold for plant life.

3. Plant-food elements.[1] — While the physical condition of the soil has tremendous influence on plant growth, the food elements must first be considered, since their availability is so closely related to the factors that function in soil formation. Ten elements are usually considered as absolutely necessary for plant growth. They may be classified as follows: —

[1] For a complete discussion of the plant-food elements as related to the plant, see Russell, E. J. Soil Conditions and Plant Growth, Chapter II, pp. 30-45. New York City. 2d edition, 1915.

Elements obtained from air or water	Elements coming directly from the soil itself[1]	
Carbon	Nitrogen	Magnesium
Oxygen	Phosphorus	Iron
Hydrogen	Potassium	Sulfur
Nitrogen	Calcium	

Carbon is obtained very largely by the plant directly from the air as carbon dioxide (CO_2), while oxygen comes directly from the atmosphere or from water, which is also the source of at least a part of the hydrogen utilized in vegetative growth. The other elements, except in the case of leguminous crops, are taken wholly from the soil solution itself.

While all these elements found in the soil must be available in order that plants may grow normally, only a very few ever become limiting factors. The three elements most likely to be lacking in a soil from a food standpoint are nitrogen, phosphorus, and potassium. They may be designated as the primary elements for plant growth. The other elements are usually present in amounts many times greater than will ever be needed by crops. Calcium, while necessary in large quantities in a soil, is largely an amendment, and very seldom may limit plant growth because of being in too minute quantity to supply the food needs of a crop. The liming of a soil is for other purposes than the supplying of calcium for plant nutrition. Sulfur is supposed, in certain soils, to limit plant growth because of its insufficiency, but ordinarily it is never found in a minimum quantity.

Nitrogen exists in the soil largely as a portion of the

[1] Sodium, silicon, and aluminium are found in plants, but are not essential to proper growth.

partially or wholly decayed organic matter present therein. It is utilized by the plant ordinarily in the form of nitrate. The atmosphere, composed of four-fifths nitrogen by volume, has been the original source of this element; and through natural processes which are continually at work the nitrogen has been transferred to the soil. The encouragement of this natural fixation, thus drawing upon the great body of gas surrounding the earth, has become of great practical importance in agricultural operations.

Phosphorus has its origin in the mineral apatite and exists in most soils largely as a tricalcium phosphate ($Ca_3(PO_4)_2$). In case of a lack of lime or of the presence of considerable quantities of humus, phosphorus may be present as ferric or aluminium phosphates or as organic phosphoric acid. Phosphorus is probably taken up by the plant as the mono- or di-calcic phosphate ($CaH_4(PO_4)_2$ or $Ca_2H_2(PO_4)_2$).

The potassium of the soil exists largely in feldspar ($K_2O . Al_2O_3 . 6 SiO_2$), in mica, or in hydrated aluminium silicates, which, while rather insoluble, supply potash to the soil solution in the bicarbonate, chloride, nitrate, or sulfate forms. It is from such compounds that the plant draws upon the soil for this element.

4. Abundance of plant-food elements. — Having considered the plant-food elements, especially those of primary importance, it is of interest to note their distribution in the earth's crust. Clarke[1] estimates the composition of the lithosphere, which makes up 93 per cent of the known terrestrial matter, as follows: —

[1] Clarke, F. W. Data of Geochemistry. U. S. Geol. Survey, Bul. 491, p. 33. 1911.

Oxygen	47.17	Sodium	2.43
Silicon	28.00	Potassium . . .	2.49
Aluminium . . .	7.84	Hydrogen . . .	.23
Iron	4.44	Carbon	.19
Calcium	3.42	Sulfur	.11
Magnesium . . .	2.27	Phosphorus . . .	.11

The briefest scrutiny of this table reveals the fact that the lighter elements are the more abundant in the earth's crust. The first four elements make up eighty-seven per cent, while the primary elements of plant growth either are lacking or are present only in very small quantities.

6. Soil-forming rocks. — As has been stated, ordinary soil is made up largely of inorganic matter which is derived from ground-up rock material. Therefore, in any study of soil origin or formation, however cursory, the attention must be directed toward geological conditions, not because of their mere geological interest but because of their ultimate bearing on soil fertility and crop growth. In the soil we expect to find, and do find, fragments of the commonest rocks, because those most exposed and those present to the largest extent at the earth's surface must be the ones to break down into soil. Therefore the commonest soil-forming rocks are the rocks that are met so commonly in the field. They may be classified broadly under three heads — igneous, sedimentary, and metamorphic. Some of the common types are as follows:

Igneous	Sedimentary	Metamorphic
Granite	Limestone	Schist
Syenite	Sandstone	Gneiss
Diorite	Shale	Marble
Diabase	Dolomite	Slate
Gabbro		Quartzite
Peridotite		

The igneous rocks furnish material for the formation of the types constituting the other groups. They may be divided in a general way into two classes—one containing a high percentage of silica and some free quartz, the other having a medium or low silica content and no quartz. The former is designated as acid, and the latter as basic since it contains a high percentage of the alkalies and the alkaline earth minerals. Granite and gabbro are excellent examples, respectively, of these general groups of rock.

The sedimentary rocks, formed from material derived from the igneous rocks, have been deposited usually under fresh- or salt-water conditions. The development of pressure has in many cases been instrumental in the consolidation of this material. The limestone and the dolomite deposited by precipitation may be expected to be comparatively soluble rocks. Shale is merely a more or less hardened clay, while sandstone varies according to the cementing material which serves to hold its sand grains together. This cement may be iron (Fe_2O_3), calcium carbonate ($CaCO_3$), or silica (SiO_2).

The action of heat, usually with pressure, on either igneous or sedimentary rocks, results in the third group, the metamorphic. Thus, granite on metamorphosis may form either a gneiss or a schist; limestone or dolomite may form marble; shale may form slate; and sandstone may form quartzite.

On examination, ordinary rock is found to be composed of one or more minerals. In other words, it is a mineral aggregate. The mineral, in turn, is a natural compound of approximately a constant chemical composition, usually displaying a crystalline form and other well-defined physical properties. In order to illustrate the com

plication that may arise, the mineral composition of some common rocks is given below:

Granite — Quartz, orthoclase, and plagioclase with mica and hornblende.

Syenite — Orthoclase and mica with hornblende and augite.

Basalt — Plagioclase and hornblende or augite with apatite, pyrite, and mica.

Peridotite — Olivine with augite, pyrite, mica, and hornblende.

Limestone. — Calcium or magnesium carbonate with traces of silica and iron.

Sandstone. — Sand cemented with iron, silica, or calcium carbonate.

This complex character of rocks has an important bearing on the question of soil formation, since the presence or absence of certain minerals may have considerable influence on the physical or chemical characteristics of the resultant soil. It is the minerals, therefore, rather than the rocks themselves, that must be looked to in a study of the great mass of inorganic matter, some active and some inactive, which makes up the bulk of ordinary soils. The question of the composition of a soil thus becomes more intensely geologic as we proceed.

8. **Soil-forming minerals.** — A great many minerals have been discovered, studied, and classified, but only a comparatively few occur in any abundance in the normal soil. Nevertheless, it may be said that practically all soils contain all the common rock-forming minerals. This is to be expected, as fragments of practically all the common rocks go to make up an ordinary soil. The

following list will give some idea of the minerals normally present in soils: —

COMMON SOIL-FORMING MINERALS

1. Quartz . . SiO_2
2. Orthoclase $K_2O . Al_2O_3 . 6\,SiO_2$
3. Plagioclase $Na_2O . Al_2O_3 . 6\,SiO_2$, $CaO . Al_2O_3 . 2\,SiO_2$ or combinations
4. Hornblende Chiefly $Ca(MgFe)_3Si_4O_{12}$ with $Na_2Al_2Si_4O_{12}$ and $(MgFe)_2 . (AlFe)_2 . Si_2O_{12}$
5. Augite . . Chiefly $CaMgSi_2O_6$ with $(MgFe)(AlFe)_2SiO_6$
6. Muscovite $2\,H_2O . K_2O . 3\,Al_2O_3 . 6\,SiO_2$
7. Biotite . . $(HK)_2\,(\overset{ii}{MgFe})_2\,(\overset{iii}{AlFe})_2\,(SiO_4)_3$
8. Olivine . $2\,(MgFe)O . SiO_2$
9. Serpentine $3\,MgO . 2\,SiO_2 . 2\,H_2O$
10. Epidote . $H_2O . 4\,CaO . 3\,(AlFe)_2O_3 . 6\,SiO_2$
11. Apatite . $3\,Ca_3P_2O_8 + (CaF_2)$ or $(CaCl_2)$ or combinations
12. Zircon . . $ZrO_2 . SiO_2$
13. Chlorite . $H_{40}(FeMg)_{23}Al_{14}Si_{13}O_{90}$
14. Calcite . $CaCO_3$
15. Dolomite . $CaCO_3 . MgCO_3$
16. Gypsum . $CaSO_4 . 2\,H_2O$
17. Talc . . $H_2O . 3\,MgO . 4\,SiO_2$
18. Hematite . Fe_2O_3
19. Siderite . $FeCO_3$
20. Limonite . $2\,Fe_2O_3 . 3\,H_2O$
21. Kaolinite . $2\,H_2O . Al_2O_3 . 2\,SiO_2$
22. Zeolites . Complex hydrated aluminium silicates of Ca, K, and Na as Philolite $(CaK_2Na_2)Al_2Si_{10}O_{24} . 5\,H_2O$

There are certain of these minerals that merit especial attention because of particular attributes which they may impart to a soil. Quartz, for example, is very common in all soils, making up usually from 85 to 90 per cent of their composition. It is a makeweight material, however, as it is used to a very slight extent by most plants; but it adds a stability to the soil that perhaps the soil would not otherwise have, and this function is of considerable significance. Of greater importance from the plant-food standpoint are the feldspars, of which orthoclase is probably primary because it is the source and storehouse of the soil potash. Acted upon by physical and chemical agencies, it slowly supplies the soil solution with potassium, which in turn nourishes the plant. The micas also may furnish considerable potash for crop growth. The plagioclase, instead of being rich in potassium, as the formula indicates, contain the more basic elements, calcium and magnesium, as also do the pyroxenes and amphiboles represented by augite and hornblende. Olivine and serpentine, also silicates, are particularly rich in magnesium. Practically all the phosphorus in the soil, either organic or inorganic, has had its origin in the mineral apatite; yet this mineral is present in rocks and soil usually in very small quantities, making up not more than 0.6 per cent of the bulk of igneous rocks. Moreover it is a rather insoluble material. This fact, together with the small quantities occurring in soil-forming rocks, may account for the need of phosphorus in many otherwise fertile soils.

Calcium, so important as a basic material in soil, may be supplied to a certain extent by other minerals besides those already named — calcite, dolomite, and gypsum being perhaps the most important, especially the calcium

carbonate in either the crystalline or the amorphous forms. Plenty of calcium in a soil tends not only to better physical conditions, but also to improve chemical reactions and biological activity. The iron of the soil minerals is of importance in its color relationships, for when oxidized to the hematite form a bright red may be imparted, while a yellow may result if limonite is produced. Color has great significance in a general estimate of soil productivity and is always an important factor in soil identification and survey. The tendency of most iron compounds in the soil is toward the hematite or the limonite form when subjected to oxidation and hydration.

Kaolinite is a product of rock decomposition and is considered to be of considerable importance in most clays or clay loams. It is almost always impure and in this form is designated as kaolin. Kaolin and the soil zeolites, which are hydrated aluminium silicates carrying chiefly calcium, sodium, and potassium, are really the end products of rock decay and therefore are secondary minerals. Consequently they must always be considered in any study of soil formation or of soil utilization, particularly as they may serve to enrich the soil solution in plant-food held by them in physical and chemical combinations.

7. Relative abundance of minerals. — D'Orbigny[1] presents the following table as a result of his calculation on the distribution of certain minerals in the earth's crust: —

	Percentage		Percentage
Feldspars	48	Carbonates	1
Quartz	35	Hornblende, augite, etc.	1
Mica	8	All other minerals . .	2
Talc	5		

[1] Hall, A. D. The Soil, p. 16. New York City. 1907.

This agrees in general with the distribution of these minerals in the earth's surface and accounts for their universal presence in all soils.

8. **Organic matter.** — The minerals as listed account for all the elements of plant-food obtained from the soil except nitrogen, which, as already indicated, is found very largely locked up in proteid and other nitrogenous material. The incorporation of organic matter in any soil, either by natural or by artificial means, besides tending to better its physical condition also enriches it in its total, or gross, nitrogen content. Though this organic matter is so necessary in a fertile soil, its addition and thorough incorporation occurs late in the process of soil formation. Through the agency of bacteria and other organisms the organic compounds are slowly simplified, new compounds are split off, and nitrogen is introduced into the soil solution mainly as nitrate, which is one of the principal forms in which it may be used by plants growing on the soil.

9. **The soil and the plant.** — Observed from the agricultural standpoint, thus, the soil becomes purely a medium for crop production. Its composition, both mineral and organic, is of vital importance in the furtherance of such a use. All the physical, chemical, and biological agencies become directed toward this end. The study of the soil and a better understanding of its function will allow the great class of landowners not only to increase their crops, and consequently their profits, but at the same time to maintain as far as possible the fertility of our greatest national resource. A rational study of the soil should ultimately lead to a study of conservation in its bearing both to present prosperity and to the welfare of posterity.

CHAPTER II

SOIL FORMING PROCESSES

AFTER the first proper estimate of the relations between the crop and the soil, the next step is toward the mode of soil formation and the agencies concerned. As might be expected, this is a complicated problem from the fact that most rocks are so heterogeneous in their composition. The question becomes still further involved because of the many factors that are continually functioning in rock decay. This process of the breaking down of rock masses and their gradual evolution into soil is called *weathering*.[1] Rock weathering may be defined specifically as the changes that rock masses undergo due to the physical and chemical activities of atmospheric agents. Everything on the earth's surface is seeking a more stable condition, and therefore, from a geological standpoint, is continually changing. If a soil represents a more stable condition than the exposed rock, the rock slowly evolves toward the soil. Again, if a soil presents constituents not wholly stable, that soil will change by an elimination or an alteration of these components. The soil, then, is a geologic unit. It is a transition product from one condition to another.

This weathering, which brings about such changes and is such a factor in the modifications of our topography, is

[1] For a complete discussion of weathering, see Merrill, G. P. Rocks, Rock Weathering, and Soils. New York. 1906.

very superficial and affects the earth to but relatively shallow depths. However, from the fact that it provides a medium for crop growth and at the same time is largely instrumental in maintaining the fertility of this medium, its agencies and processes become of great significance.

The forces of weathering, while very diverse not only as to action but also as to product, permit of an outline so clear that the true relationships at once become apparent. This classification may be made under two heads, mechanical and chemical, as follows: —

Forces of weathering

I. Mechanical changes, or disintegration
   - *A.* Erosion and denudation
     - Water, wind, ice
   - *B.* Temperature
     - Heat and cold, and frost
   - *C.* Plants and animals

II. Chemical changes, or decomposition
   - *A.* Oxidation and carbonation
   - *B.* Deoxidation
   - *C.* Hydration
   - *D.* Solution

10. Water. — The three great agencies of erosion and denudation are water, wind, and ice. They are instrumental not only in the breaking up of rocks, but also in transporting the resultant materials. Water is especially of importance, as its denuding effects are very rapid when viewed over geological periods. It is estimated that the United States is being planed down at the rate of one inch in seven hundred and sixty years. This is rapid enough to dig the Panama Canal in seventy-three days.

The water, in order to be a successful cutting agent, must be laden with sediment, so that its carrying power largely determines its power of erosion. In other words, it must be armed.

From the time when the raindrops beat down on a surface until they have been gathered into rivulets and streams and finally discharged into the ocean, they are engaged in moving the detrital matter already produced. The Mississippi River is working fast enough at the present time to reduce the continent of North America to sea level in four million years. The Appalachian Mountains, born in Paleozoic times, have lost vastly more material than now remains for us to view. Our river and lake soils are due to the cutting and carrying power of the streams. The deltas, and the marine soils of the Atlantic and Gulf coasts, afford other examples of such effects. The continual pounding and grinding of waves are no mean factor in rock disintegration. The rounding of the sands is a mute evidence of this great force.

11. Wind. — The wind as a soil-forming agent has, like water, two phases of action — erosive and transportive. Sweeping over the land in dry weather, it has the power of picking up innumerable fine particles which may abrade rocks very noticeably over a term of years. The fluting of exposed rocks, especially in arid regions, the undermining of cliffs, and the polishing of stones to a smoothness equal to that of glass, are frequent occurrences. The roughening of windowpanes in houses near the seashore during severe storms, and the illegibility of old tombstones, are of common record. Great areas of soil have been deposited by winds, especially in the United States. The loess of the Mississippi Valley and

the adobe of the Southwest owe their origin, at least partially, to the carrying power of wind at a time when aridity existed over all this area.

12. Ice. — When in large bodies, as in glaciers, ice exerts a tremendous grinding power. Glacial ice, by its mobility and motility, adapts itself to all topography, and as it moves slowly forward it grinds and scours and abrades even the hardest rocks. The great masses of pebbles and rocks which are picked up and imbedded by glaciers, especially in their lower surfaces, increase their cutting power many fold. The effect of glaciers is of particular interest because of the fact that all of the northern part of the United States was covered at one time with a great ice sheet, and our northern soils are due either directly or indirectly to the advances and retreats of this ice sheet. Formed in northern latitudes due to a change in climatic conditions, the ice sheet slowly covered many thousands of square miles of territory, and as the ice was usually several thousand feet thick, hills, and often mountains, were overridden. Their tremendous weight made the grinding action almost irresistible. In the retreat, or melting back, of the ice, a mantle of this ground up and well-mixed material was deposited as soil; while the streams flowing from its front, or into glacial lakes, were furnished with heavy sediments for distribution in other regions.

13. Heat and cold. — The changes in temperature of the air, and the soils and rocks, tend vastly to augment the effect of the denuding agents. Constant expansion and contraction is productive of weakness and ultimate physical breakdown. Heat is conducted slowly through rocks, thus leading to differential heating and unequal expansion or contraction. Rocks, as already noted, are

usually mineral aggregates, and these minerals vary in their coefficients of expansion. With every change of temperature, differential stresses are set up which ultimately must produce a considerable effect. When the separate minerals expand they expand differently, and when they contract they never again assume quite their former relationships to one another. Thus crevices, cracks, and rifts are created in rocks, especially those of heterogeneous mineral composition. The expansion coefficient of granite is .0000048 of an inch to a foot for every degree Fahrenheit, while that of marble is about .0000056 of an inch. This seems to be very slight, but it must be remembered that under natural conditions large surface areas of rock are concerned. A sheet of granite 100 feet long will expand one-half an inch with a change of 75° Fahrenheit, which is not an uncommon variation of temperature in arid regions or high altitudes. This leads to chipping, flaking, and exfoliation. The rock fragments may range from microscopic sizes to large blocks, which are often split off with great violence.

14. Frost. — Great as is the action of a simple change of temperature, its effects become many fold more apparent when water is present. We then have the action of frost. The cracks and crevices made by heat and cold will in a humid region become filled with water. This moisture, on freezing, exerts a very great force. The expansive power of water passing from the liquid to the solid state is equal to about 150 tons to a square foot, which is equivalent to the weight of a column of rock about a third of a mile in height. Moreover, most rocks contain a certain amount of water in themselves. This water is recognized in excavation operations as quarry water. The passage of the quarry water to a solid state

must result most disastrously to the physical condition of the rock. This action of frost is by no means complete when the rock is fined mechanically to a soil, but is continued on the soil itself. Such further fining is of the greatest importance in bettering the physical condition of the soil, and is usually designated as a wetting and drying and freezing and thawing process. It is to such forces, more than to any other action, that the farmer owes the good tilth of his soil.

16. Plants and animals. — Plants and animals unite their forces with those already mentioned to bring about further physical change. Unlike the modifications due to erosion, denudation, and temperature, these agencies affect the soil to a greater extent than they affect the parent rock. In other words, they begin their work after the minerals have been reduced, at least partially, to the form of a soil. Simple plants, as mosses and lichens, will develop readily on rock ledges and coarse rock fragments. They send their rootlets into the crevices and exert a prying and loosening effect. They also catch dust, provide humus, and gradually accumulate a soil in which higher and still higher species of plants may grow. Their chemical effects, especially regarding solution and oxidation, aid in this disintegration. The distribution of organic matter through the soil by the extension and death of plant roots is of no mean importance in soil fertility. Bacteria also may be a factor in rock decay, not only through their action on the humus material but also through a direct attack on the rocks themselves. Their influence, however, is probably mostly chemical.

Animals also effect the fining of rock fragments and soils, from their burrowing and mixing tendencies. Such rodents as gophers and squirrels open up the soil, thus

providing better circulation of air and water. This brings about a deeper and more effective action of the other physical agencies of weathering. Earthworms produce similar effects. Their holes provide channels for ready drainage, and large quantities of soil are brought to the surface yearly by them. Darwin estimates that this amounts to as much as one or two inches in a decade.

16. Oxidation and carbonation. The physical and chemical forces do not act alone, but, as a general thing, combine in their effects. Thus one set of factors aids and accelerates the other. Scarcely has the disintegration of a rock begun, then, before its decomposition is also apparent. Of the chemical forces oxidation is usually, especially near the surface of the earth, the first to be noticed. It is perceptibly manifested in rocks carrying iron, and consists in such a change that the added oxygen may be accommodated. Sulfides readily succumb and become oxides, while these same oxides are prone to take up oxygen to their fullest extent. This oxidation is disclosed by a discoloration of the rock, which is first streaked and stained with iron oxide but at last changed to a uniform ochre. The change may be exemplified by the following reactions: —

$$2\,FeS_2 + 7\,O_2 + 4\,H_2O = 2\,FeO + 4\,H_2SO_4$$
$$4\,FeO + O_2 = 2\,Fe_2O_3 \text{ (red)}$$

While not all the minerals contain iron, enough of them do to impart a fatal weakness to most rocks. The ferrous oxide (FeO), being soluble, is washed out and the rock is creviced and crumbled. A way is now open for more energetic physical and chemical decay.

With the oxidizing action there is also the influence of

carbon dioxide (CO_2), which is universally a constituent of air and is a product of the decaying vegetable matter present in most soils. This means that the water circulating among rock fragments, especially those of a soil, is heavily charged with this compound. The carbonation may be illustrated as follows. —

$$2\,FeS_2 + 7\,O_2 + 4\,H_2O + 2\,CO_2 = 2\,FeCO_3 + 4\,H_2SO_4 \text{ or}$$
$$2\,NaOH + CO_2 = Na_2CO_3 + H_2O$$

17. Deoxidation. — Deoxidation is an opposite reaction to oxidation, being a loss of oxygen either to the air or to some other compound. With hematite it might take place as follows. —

$$2\,Fe_2O_3 - O_2 = 4\,FeO$$

Under normal conditions, however, it is not a very important factor, since most rock fragments and soil are fairly well aërated, at least too well aërated to allow this reverse process to occur. In poorly drained soil or in soil very rich in humus and carrying organic acids it may occur, and is usually manifested by the development of blue and gray colors, indicating that a reduction has taken place. The bleaching of sands, sandstones, and clays may be due partially to this, and also to a removal of the ferriferous salts in solution. Some subsoils display this phenomenon. The average farmer, however, need not concern himself with the injuries that may result from deoxidation.

18. Hydration. — Hydration usually accompanies oxidation, but when occurring at great depths it may be practically the only change the minerals have undergone. Minerals, especially feldspars, become clouded and lose their luster on the assumption of chemically combined

water. There is also a considerable increase in bulk, this being often as much as 88 per cent during the transition of a rock to a soil. Hydrated minerals, while apparently sound, quickly succumb when exposed to forces of weathering which are more superficial in their effects. Carbonation and oxidation usually take place as correlative actions with hydration. A simple example of hydration is shown in the change of hematite to limonite, which occurs in practically every case when iron is allowed to oxidize from pyrite or a simpler oxide to the higher forms: —

$$2\,Fe_2O_3\ (\text{red}) + 3\,H_2O = 2\,Fe_2O_3 . 3\,H_2O\ (\text{yellow})$$

19. **Solution.** — As it is now quite evident that weathering, especially the chemical manifestations, is largely a simplification of compounds, and that water is almost universally present, some solution must occur. These simple materials are particularly prone to enter solution because of the presence of carbon dioxide, which, by acidifying the soil water, intensifies its solvent action to a considerable extent and consequently increases its power as a weathering agent. The atmosphere contains amounts of this gas ranging from 3.82 to 4.48 parts in 10,000, while considerable amounts are brought down on the rocks and the soil in snow and rain. The carbon dioxide evolved directly into the soil water from decaying organic matter also aids in keeping the soil charged with this gas. This means, then, that solution is largely a process of carbonation, especially after the soluble constituents have been thrown out into the soil solution. It is evident that oxidation, carbonation, hydration, and solution act in unison to bring about the chemical decay of the rock and the soil. This combined action may be represented

by showing the various stages that orthoclase may undergo in producing a residual clay:—

$$KAlSi_3O_8 + HOH = HAlSi_3O_8 + KOH$$
$$2\,KOH + CO_2 = K_2CO_3 + H_2O$$
$$HAlSi_3O_8 - 2\,SiO_2 = HAlSiO_4 \text{ (kaolinite)}$$

The silica in this case may become quartz or colloidal silica, or, what is more probable, may unite with certain elements to produce complex hydrated silicates.

20. A general statement of weathering. — The question of rock weathering is complicated because no one action can be considered alone. All forces are acting together, tending to produce a great complex of reaction and interaction. No amount of explanation or speculation can ever fully clarify the question as to the formation of a soil from a parent rock. Nevertheless, knowing in general the separate forces and reactions produced, we may formulate the phenomenon in a general and superficial way. The change that a rock undergoes in the formation of a residual clay is first a physical breaking down accompanied by chemical changes, which consist in the hydration of the feldspars, the oxidation of the iron, and the solution and carbonation of the soluble bases.

21. Factors affecting weathering. — It is readily to be seen that the activity of the various agencies of weathering will be modified by certain factors which determine not only the kind of rock decay but also its rate. Of these, climate is probably of the greatest importance. The difference in the weathering in an arid region as compared to that in a humid region will illustrate this point. Under arid conditions the physical forces will dominate and the resulting soil will be coarse. Freezing and thawing, heat and cold, the action of the wind, and

the effect of animals, will be almost the sole agents. In humid regions, however, the forces are more varied and practically the full quota will be at work. Chemical decay will accompany the disintegration, and the resultant product will be finer and more minutely divided. The separate minerals will show also the change of color and loss of luster due to the decomposition of some of their essential elements. The same rocks, then, will behave differently under different climatic conditions. A granite, for instance, is a very insoluble rock as compared with a limestone, and in a humid region where chemical agencies are dominant it would be markedly more resistant. If, however, these two rocks are placed under arid conditions where the physical forces are potent, particularly as regards change of temperature, the comparison is different. The limestone, being homogeneous, is not affected by atmospheric changes; but the stresses set up in granite due to differential contraction and expansion must ultimately reduce it to fragments.

As weathering is confined to the very surface of the earth, the exposure or position of a rock will determine the kind and the rate of decay. If the rock is very deep below the surface, only hydration may occur; while if it exists as an exposed ledge, the full force of the weathering agents will be sustained. If the débris of the decayed rocks is not removed, this serves as a blanket for the protection of the rocks below. The transportive powers of weathering are important in maintaining a clean surface for action.

The texture of the rock is also a factor. Other things being equal, a coarsely crystalline rock will disintegrate and decompose more rapidly than one of finer grain. The coarser the grain, the larger the amount of interstitial

space and the greater the encouragement to physical agencies. As physical changes open the way for chemical decay, coarse texture will ultimately encourage decomposition as well as disintegration.

Lastly, the disruptive forces of the rock will be influenced by the chemical composition of the minerals and the mineral composition of the rock. A rock made up of minerals that offer but little resistance to decay will naturally reduce readily and quickly to a soil. Rocks that very largely bear minerals which are refractory in their nature, however, may never decompose far enough or rapidly enough to give a soil of any agricultural significance. The next step, then, in the study of soil formation is a consideration of the relative resistance of the minerals and the rocks.

22. The law of mineral and rock decay. — Considerable work has been done on the comparative solubility of minerals both in pure and carbonated water, but in most cases it has proved somewhat inconclusive. Nevertheless we are able, by consulting the work of Müller,[1] Clark,[2] Daubree,[3] and others, to arrange some of the commoner minerals in the order of their solubility, the most resistant minerals heading the list: —

1. Quartz	6. Epidote	11. Apatite
2. Muscovite	7. Serpentine	12. Olivine
3. Biotite	8. Talc	13. Calcite
4. Orthoclase	9. Hornblende	
5. Plagioclase	10. Augite	

[1] Müller, R. Solution of Rocks in Carbonated Water. Jahrb. d. k. k. Geol. Reichsanstalt, Vol. XXVII, p. 25. 1877.

[2] Clark, F. W. Data of Geochemistry. U. S. Geol. Survey, Bul. 330, p. 401. 1908.

[3] Daubree, A. Solubility of Orthoclase. Études de Géol. Expérimentale, pp. 27 and 252. Paris, 1867.

The next step is to deduct some general law which can be shown to govern the resistance of these minerals. Such a statement would aid considerably in the making of general deductions regarding weathering. The siliceous content of some of these minerals, taken in the order as above, throws considerable light on this phase:—

	Per cent of SiO_2		Per cent of SiO_2
Quartz	100	Hornblende	45
Orthoclase	65	Olivine	41
Plagioclase	55	Calcite	trace

Another case might be cited in a comparison of the chemical composition of anorthite, hornblende, and olivine:—

Anorthite . $CaAl_2Si_2O_8$

Hornblende . $Ca(MgFe)_3(SiO_3)_4$ with $\begin{cases} Na_2Al_2(SiO_3)_4 \text{ and} \\ (MgFe)(AlFe)_2SiO_6 \end{cases}$

Olivine . . $(MgFe)_2SiO_4$

It is to be noted that immediately as the resistance of a mineral declines, its content of silica decreases and the percentage of the basic constituents increases. Silica and aluminium, then, mark resistance to decay; while calcium, magnesium, sodium, potassium, and iron function in increasing susceptibility to decay. The law of mineral resistance may be formulated as: "The more basic a rock becomes, the more rapid is its decomposition; and the more acid, the less marked is its decay."[1]

This general law certainly should apply to rocks that are made up of the minerals listed above. One example will show this clearly. The igneous rocks, as already stated, may be divided into two groups, acid and basic.

[1] Buckman, H. O. The Formation of Residual Clay. Trans. Amer. Ceramic Soc., Vol. XIII, p. 368. February, 1911.

This acidity and basicity is determined by the presence of silica and the alkalies, respectively, as carried by certain essential minerals. Suppose we name some representative igneous rocks in the order of their acidity, and list some of the minerals carried by them: —

1. Granite . . . Quartz, orthoclase, and mica
2. Diabase . . . Plagioclase, mica, hornblende, or augite
3. Peridotite . Principally olivine

It is to be seen that the minerals contained by granite are more resistant than those carried by either the diabase or peridotite, while the olivine of the last group is near the foot of the list when the minerals are arranged in the order of their resistance.

The following data[1] bear out the argument presented above as to the relative resistance of rocks: —

Proportional Amounts of Three Rocks Soluble in Boiling Hydrochloric Acid and Sodium Carbonate Solution

	Peridotite	Diabase	Granite
SiO_2	21.51	10.59	9.49
$Al_2O_3Fe_2O_3$	12.60	15.85	8.38
CaO	1.07	3.09	.60
MgO	.40	2.20	.71
K_2O	.28	1.21	1.68
Na_2O	5.45	.56	1.20
	41.44	33.50	22.02

It is evident, then, that the law of mineral resistance applies to rocks as well as to the separate minerals, although its application thereto is much more complex and difficult to interpret.

[1] Merrill, G. P. Rocks, Rock Weathering, and Soils, p. 366, New York. 1906.

23. Special cases of weathering. — The weathering of granite and limestone under different climatic conditions has already been compared. The changes that take place in these rocks as they are evolved to residual clays may now be considered. The following analyses serve to show on what elements the losses are likely to be most serious during the process: —

FRESH GRANITE AND ITS RESULTANT CLAY[1]

	Rock	Clay	Percentage Loss
SiO_2	60.69	45.31	52.45
Al_2O_3	16.89	26.55	00.00
Fe_2O_3	9.06	12.18	14.35
CaO	4.44	00.00	100.00
MgO	1.06	.40	74.70
K_2O	4.25	1.10	83.52
Na_2O	2.82	.22	95.03
P_2O_5	.25	.47	00.00
Ignition	.62	13.75	Gain

VIRGINIA LIMESTONE AND ITS RESIDUAL CLAY[2]

	Rock	Clay	Percentage Loss
SiO_2	7.41	57.57	27.30
Al_2O_3	1.91	20.44	00.00
Fe_2O_3	.98	7.93	24.89
CaO	28.29	.51	99.83
MgO	18.17	1.21	98.38
K_2O	1.08	4.91	57.49
Na_2O	.09	.23	76.04
P_2O_5	.03	.10	68.78
CO_2	41.57	.38	99.45
H_2O	.57	6.69	Gain

[1] Merrill, G. P. Bul. Geol. Soc. Amer., Vol. 8, p. 160. 1897.
[2] Diller, J. S. U. S. Geol. Survey, Bul. 150, p. 385. 1898.

Soils have resulted in both cases from the decay of these rocks. In the case of the granite the resulting soil was a deep red clay, with quartz grains present. The soil from the limestone was a plastic clay, high in silica and aluminium. Leaching has probably gone on to a very great extent in both soils. It is noticeable also that the basic constituents have suffered the greatest losses, especially calcium, magnesium, sodium, and potassium. The carbonate has almost wholly disappeared from the limestone clay, showing that a limestone soil may not necessarily be rich in lime. As a matter of fact, the chances are that if it is residual it will be lacking in that compound. When shown diagrammatically (See Figs. 1 and 2), the changes that the parent rocks have undergone chemically in forming a clay will become apparent.

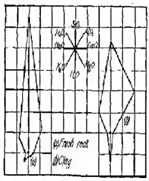

FIG. 1. — Diagrammatic representation of the chemical composition of fresh granite and its residual clay. See analyses above.

As shown by the diagrams, the soil from the granite does not differ greatly from the original rock, except in loss of bases, assumption of water, and increase of organic

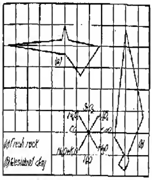

Fig. 2.—Diagram showing the chemical composition of Virginia limestone and its residual clay. See analyses above.

matter. The residual clay from the limestone presents greater differences, due to the almost entire disappearance of calcium carbonate. The diagrams for the two clays resemble each other fairly closely in spite of their widely differing sources. Because weathering causes the persistence and accumulation of silica, aluminum, and iron, and a loss of the basic materials, all soils as they weather tend to approach a similar composition. Yet, owing to a difference in the adjustment of the forces at work and in the time element, no two soils will ever be exactly alike. Soils will differ, then, from the original rock and from one another according to the intensity

and character of the weathering and the constitution of the parent minerals.

34. Practical relationships of weathering. — Weathering processes result in a general simplification of compounds. Their action first affects the rock, with the result that a soil is produced; but they still remain active in the soil after it is in a condition to support plants. The physical agencies especially tend to loosen and fine the soil, contributing largely to its tilth. The farmer encourages such influences by plowing his land and by other operations. Were it not for such weathering action, the soil would become physically unable to afford foothold for plants. The continued chemical changes resulting in solution and carbonation provide a soil water rich in plant-food nutriment. Weathering, then, by a slow process over geologic periods has provided us with soil, and by the same slow process is maintaining the fertility of this creation. The encouragement and control of such an agency is of no small importance in agricultural practice.

CHAPTER III

THE GEOLOGICAL CLASSIFICATION OF SOILS

WEATHERING must be considered as affecting soils both *in situ* and in motion. This gives two general classes of materials — those that have not been shifted far from their place of origin, and those in the formation of which the transporting agencies have been instrumental. These two general groups, designated as sedentary and transported,[1] are subject to considerable subdivision, as follows: —

- Sedentary
  - Residual
  - Cumulose
- Transported
  - Gravity — Colluvial
  - Water
    - Alluvial
    - Marine
    - Lacustrine
  - Ice — Glacial
  - Wind — Æolian

25. Residual soils. — This group of soils covers wide areas of our arable regions and comes from many kinds of rocks. Residual soils are old soils, the oldest with which we have to deal in agricultural operations. Since a

[1] See Trowbridge, A. C. A Classification of Common Sediments. Jour. of Geol., Vol. 22, No. 4, pp. 420-436. 1914.

residual soil is formed *in situ*, the rocks that underlie it, if sound, show the character and composition of the rocks from which the soil was actually a product. In such soils the changes that a rock undergoes in forming a residual clay are to be studied to the best advantage. An examination of the various grades of material that are found overlying the country rock (Fig. 3) in an area where

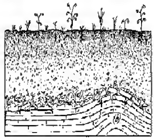

Fig. 3. The gradual transition of country rock into residual soil by weathering *in situ*.

this residual mantle exists, reveals more or less accurately the gradations from rock to soil. Residual soils, besides being old soils, are usually nonstratified and present a heterogeneous mass of material. Since they have been subjected to leaching over vast periods, a very large amount of the soluble materials have been washed out, tending to leave high percentages of the persistent materials, such as silica, iron, and aluminium. An analysis of an Arkansas limestone, its residual clay and the calculated percentage loss of the various constituents present in the fresh rock, illustrates this point:—

ARKANSAS LIMESTONE AND THE RESIDUAL CLAY[1]

	FRESH ROCK	CLAY	PERCENTAGE LOST
SiO_2	4.18	33.69	.00
Al_2O_3	4.10	30.30	11.35
Fe_2O_3	2.55	1.90	89.58
MnO	4.23	14.98	57.59
CaO	44.79	3.91	98.90
MgO	.30	.26	99.38
K_2O	.35	.96	60.29
Na_2O	.16	.61	53.28
CO_2	34.10	.00	100.00

The vast age of such soils tends to bring about great oxidation, so that most of the iron has changed to hematite and limonite. Since almost all soils contain considerable iron, the prevailing colors of residual soils are reds and yellows, depending on the degree of oxidation and hydration. Grays and browns may exist, however, where iron has been lacking or oxidation has been feeble. In texture such soils usually present very fine conditions. Having been attacked by both the physical and the chemical agencies, the particles have been reduced to a very fine state of division. Over residual areas the heavier soils predominate, as silts, silt loams, clays, and clay loams. Very often sand or chert may be present, having been a constituent of the original rock mass.

An examination of the particles of a residual soil usually shows them to be in an advanced stage of decay. The feldspars have lost their luster and have become opaque. The iron has become oxidized, and the soluble bases have

[1] Penrose, R. A. F. Ann. Rept. Geol. Survey Arkansas, Vol. I, p. 192. 1891.

either disappeared or changed their combinations to more stable forms. The tendency of all soils is toward a condition of equilibrium, and consequently they approach, but never reach, a common composition. This does not apply to their productivity, because many other factors besides chemical composition go to determine cropping power. Residual limestone soils, therefore, become poorer and poorer in lime as their age increases. The organic matter of residual soils largely depends, in amount and condition, on climatic factors. If rainfall and temperature, for instance, are favorable for the rapid and continued development of a natural vegetation, the soil will be rich in humus, so rich at times as to mask to a certain extent the red color so characteristic of such soils. If plants do not grow well on this soil, however, it will be low in organic matter and probably in poor physical condition, so vital is humus to a proper foothold for plant life. Two residual soils coming from the same kind of rocks may vary rather widely in their general characteristics, especially as to crop productivity.

28. Distribution of residual soils. — Residual soils are of wide distribution in the United States,[1] particularly in the eastern and central parts. A glance at the soil map of this country (See Fig. 4) shows four great provinces — the Piedmont Plateau, the Appalachian Mountains and Plateaus, the Limestone Valleys and Uplands, and the Great Plains Region. The age of these soils varies in the order named, showing that while they are very old as compared with other soils yet to be discussed, there may be vast periods of geologic time between their beginnings. As a matter

[1] For a full discussion of the origin and characteristics of the soils of the United States, see Marbut, C. F., and others. U. S. D. A., Bur. Soils, Bul. 96. 1913.

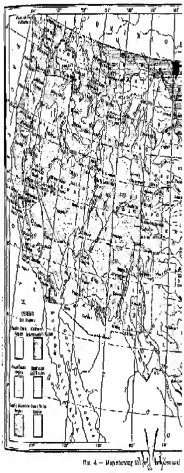

Fig. 4. — Map showing th

of fact, there is probably a greater difference in age between the soils of the Piedmont Plateau and those of the Great Plains Region than has elapsed since the latter were formed. The soils of the Piedmont Plateau have been formed mostly from gneiss and schist. In fact, the Piedmont Plateau is the remnant of the old continent, Appalachia, which was in existence in early Cambrian times. The rocks of the Appalachian Mountains and Plateaus are limestone, sandstone, and shales. The Great Plains Region presents limestone, sandstone, and shale of the Cretaceous, Permian, and Carboniferous ages, besides much unconsolidated material. The soils of these provinces, extending as they do over great areas, vary within wide limits due to rock formation, climatic conditions, and age; yet certain common characteristics, as already pointed out, are exhibited by all.

27. Cumulose soils. — This type of soil is of a very different character from the one just under discussion, being made up largely of organic matter with the mineral constituents of secondary importance. At relatively recent periods shallow lakes, ponds, and basins were formed, partly by stream action, partly by marsh conditions along sea or lake coasts, or, what is commoner in the northern part of the United States, by glaciation. Any basin that contains water throughout the year serves as a place for the formation of cumulose soil. The highly favorable moisture relations along the banks and shores of such standing water encourage the growth of many plants such as algae, moss, reeds, flags, grass, and the like. These plants thrive, die, and fall down only to be covered by the water in which they were growing. The water shuts out the air to a large extent, prohibits rapid oxidation, and thus acts as a preservative for the rapidly collect-

ing organic matter. Year after year this process goes on, and year after year the bed of cumulose material becomes deeper and deeper. Large shrubs, and even forests, often grow on such land. Time and the lack of water are the factors that may limit the depth of such beds. Accumulations of this nature are found dotted over the entire country. Their size may vary from a few acres to several thousand. Along streams the old abandoned beds offer a common opportunity for the beginning of such accumulations. Along large bodies of water, marshes, either salt or fresh, may allow the process to go on. Shallow basins scraped and gouged out by advancing glaciers are frequently occupied by such material. In the last-named case the beds are more or less independent of topography, and may be found on hillsides, or even on hilltops, as well as in the lower lands.

Cumulose materials may be grouped under two heads, peat and muck. The only difference is in their stage of decay. In peat the stem and leaf structure of the original plants can still be detected, and identification is quite possible. In muck, however, the putrefaction and decay have gone so far that the plant tissue has lost its identity as such and is merged into that complicated and indefinite material called humus. The composition of peat and muck may be much altered by the washing-in of mineral matter from above. In some cases the beds may be from 80 to 85 per cent organic, while in other cases, due to this foreign material, the percentage may drop to as low as 15, giving a black or swamp marsh mud.

The following analyses illustrate the composition of representative cumulose soils: —

	1	2	3
Mineral matter	31.60	24.79	80.40
Organic matter	68.40	[illegible]	15.77
Nitrogen	2.63	2.03	—
P_2O_5	.30	.19	.15
K_2O	.17	.15	.06
Moisture		2.68	3.83

1. Muck.—Huston, H. A. Muck. Composition and Utilization. Wis. Exp. Sta., Bul. 13. 1891.
2. Muck.—Rept. Can. Exp. Farms, 1910. Rept. of chemist, p. 180.
3. Marsh mud.—Rept. Can. Exp. Farms, 1910. Rept. of chemist, p. 137.

Muck soils, while usually not of large extent, become of extreme value when drained, especially if they are near a good market. They are of particular value in trucking operations, being adapted to such crops as onions, celery, lettuce, and the like. Usually they must not only be provided with drainage, but also be treated with fertilizers carrying phosphorus and, especially, potash. It is also a good practice to start vigorous decay by the application of barnyard manure, as the nitrogen carried by muck soils is usually not very readily available to plants. In many cases muck and peat may be underlaid at varying depths by marl, which is a soft, impure calcium carbonate. Before and at the beginning of the organic accumulation these basins were inhabited by Mollusca, which at death deposited their shells on the bed of the inclosure. These shells are now found in a more or less fragmentary condition, usually mixed with sand and clay and covered to a varying depth with peat or muck. Such material, because of its richness in lime, is valuable

as a soil amendment, and often where it is found pure enough in quality and in sufficiently large quantities it is handled commercially. When it contains large amounts of phosphorus, as it does in some cases, it may be used as a fertiliser. The following analyses[1] show the general character of this soil: —

	1	2
SiO_2	26.28	8.66
$Al_2O_3 . Fe_2O_3$	3.02	2.30
CaO	37.52	48.51
MgO	.12	1.96
K_2O	.28	.23
Na_2O	.25	.20
P_2O_5	.40	Trace
CO_2	29.42	38.80
Ignition	4.17	.25

28. Colluvial soils. — This class of soil is not of great importance, first because of its small area and its inaccessibility, and secondly because it is usually a coarse, loose soil, rather unfavorable for plant growth. It is formed, as its name indicates, in regions of precipitous topography, and is made up of fragments of rocks detached from the heights above and carried down the slopes by gravity. Talus slopes, cliff débris, and other heterogeneous rock detritus are examples of colluvial soil. Avalanches are made up largely of such material. As the physical forces of weathering are most active in the formation of these soils, the amount of solution and oxidation is small. The upper part of the accumulation

[1] Kerr, W. C. Geology of North Carolina, Vol. I, p. 195. 1875.

exhibits this isolated physical action to the greatest extent, the particles being angular, coarse, and comparatively fresh; farther down the slope the material may merge by degrees into ordinary soil. Such soils are usually shallow and stony, and approach the original rock in color unless large amounts of organic matter have accumulated (Fig. 5).

FIG. 5. — Diagram showing the formation of a colluvial soil. (a), bed rock; (b), dismantled cliff; (d), coarse unproductive talus; (p), soil capable of bearing plants.

29. Alluvial soils. — In considering the importance of water as a weathering agent, it was found that it had both cutting and transporting powers. The alluvial

soil is a direct result of both these activities. The carrying power of water varies directly as the sixth power of its velocity; so that a doubling of the velocity increases the transportive ability sixty-four times. It is estimated[1] that water flowing at the rate of three inches a second will carry only fine clay, but if this rate is increased to twenty-four inches a second, pebbles the size of an egg will be moved along the stream bed. Any checking of the velocity of a stream will cause it to deposit the material carried in suspension, the larger particles first and the finest when the current becomes very sluggish. This brings about one of the important characteristics of an alluvial soil, its stratification. Wherever material is being laid down by water this phenomenon is exhibited, due to the rapid changes in velocity. As a stream approaches nearer and nearer to its outlet, its bed becomes less and less inclined and the current more and more sluggish. This tends toward an aggrading of the stream bottom from the deposited material. Such a condition naturally increases the probability of overflow in high water. Overflow at a time when the stream is carrying its maximum of sediment causes the deposition of a thin layer of soil over the areas covered by the water. This soil is stratified according to the conditions under which it was laid down, the finer particles usually being carried farther and often deposited in slack water or lagoons. Also, a stream on a gently inclined bed may begin to swing from side to side in long, gentle curves, due to the deposition of alluvial material on the inside of the curve and the cutting by the current on the opposite bank. This results in oxbows, lagoons, and similar inclosures,

[1] Geikie, A. Text Book of Geology, p. 380. New York. 1893.

ideal for the deposition of alluvial matter. Deltas are another good example of alluvial deposits, whether occurring in ocean, gulf, or lake. Due to a change in grade, a stream may cut down through its already well-formed alluvial deposit, leaving terraces on one or both sides. Often two, or even three, terraces may be detected along a valley, marking a time when the stream bed was at these elevations. On the lower slopes of hills bordering valleys, the colluvial deposits may touch or even mingle with the alluvial, and furnish a stream with some of its detritus.

Alluvial soils, then, are found as narrow ribbons along streams. They are always young soils, and are still in process of formation. Since in most cases they are deposited by slowly moving water, the texture of such soils is fine, the soils being mostly clays, silts, and fine sandy loams. Found in low lands, alluvial soils need drainage to a large extent. Because of the favorable moisture conditions these soils usually have a very large amount of organic material, as vegetation grows readily under such conditions. Considerable humus is also washed into alluvial materials at the time of their deposition. The soil is usually deep, and, because of the high organic content, universally of good physical condition, although very heavy stiff clays may be found in certain cases. The character of the soils and the rocks from which the detritus has been obtained exerts considerable influence on its character. For example, a red soil will often give rise to a reddish alluvial soil, while a soil or a rock poor in lime will certainly not be parent to a soil very much richer in that constituent.

30. **Distribution of alluvial soils.** — The distribution of alluvial soils in the United States is not wide, although

these soils exist along almost every stream east of the Great Plains Region. Their best and widest development is found, as the map indicates (See Fig. 4) along the lower Mississippi river, where they may often show a lateral extension of one hundred miles. Extensions of this band are noted along the Missouri, Ohio, and Upper Mississippi rivers. All streams flowing east exhibit areas of such soils, these areas varying with the size and velocity of the stream.

The soils of the alluvial province may be divided under two heads because of topographic differences — (1) the first bottoms, or present flood plains; and (2) the terraces, or old flood plains. These soils differ in their elevation, drainage, and age, but their general characteristics are similar; the surface features in both cases vary from a flat to a gently rolling topography (Fig. 6). Erosion, especially in the terraces, may have obliterated some of the out-

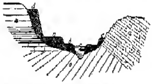

FIG. 6. — Cross-section of typical alluvial soils. (a), bed rock; (e), stream; (b), present flood plain, a recent alluvial soil; (c), flood plain terrace; (d), very old stream terrace, an old alluvial soil.

standing features. Alluvial soils, being very rich, are particularly adapted to trucking crops, although in most cases they are utilized for more extensive farming. When well drained and protected from overflow, they are the richest and most valuable of soils.

31. Marine soils. — The sediments which are continually being carried away by rivers are eventually deposited in the sea, the coarser fragments near the shore, the finer particles at considerable distances. This layer of material, varying in thickness, consists of stratified gravels, sands, and clays, and is of a rather recent age compared with the residual soils. It has not become consolidated as yet, because of insufficient pressure and time. When such material becomes raised above the sea, due to a change in land elevation, it is classified as a marine soil. It has been worn and triturated by a number of agencies. First, the forces necessary to throw it into stream suspension were active, and next it was swept into the ocean to be deposited and stratified, possibly after being pounded and eroded by the waves for years. At last came the emergence above the sea and the action of the forces of weathering in situ. The latter effects are not of great moment, since with our most important marine soils they have been at work for but a comparatively short time, speaking geologically.

32. Characteristics of marine soils. — Marine soils, while much younger than residual soils, are usually more worn and ordinarily show a less amount of the important food elements. This is because of their almost continuous contact with water from the time when they are swept into the streams until they rise above the sea level as a soil. They are generally characterized as sandy soils, because the forces to which they have been subjected have worn out and dissolved most of the minerals except quartz. This gives them a coarse texture and fits them particularly for trucking soils. Sands, sandy loams, and loams predominate usually in such soil provinces, although clays and silts may occasionally be

found. These soils are usually low in humus, and consequently must be handled with reference to the possibilities of increasing their organic content. Lack of humus makes the predominating color of the soil light, ranging from light gray to brown and dark brown. The character of these soils is governed to some extent by the origin of the sediments; different rocks, particularly if weathered under different climatic conditions, may give rise to widely different marine soils. The climatic conditions to which marine materials are subjected after being raised above the sea may also be a considerable diversifying agency.

33. Distribution of marine soils. – Marine soils are found very widely distributed in the eastern United States, and make up one of our most important soil provinces. Beginning at Long Island at the north (See Fig. 4), they extend southward along the coast in a band ranging from one hundred to two hundred miles in width. The western edge of the Atlantic coastal plain is marked by the great "Fall" Line, or the edge of the old continent Appalachia. It is from this area that most of the sediments of the Atlantic marine soils were derived. Proceeding southward, we find that Florida is practically all of marine origin, together with a great area of the Gulf coast extending westward to central Texas and having an average width of two hundred fifty miles. This gulf marine soil is considerably younger than that of the Atlantic coast. It is cut into two parts by the alluvial soils of the Mississippi, and is covered by a narrow band of alluvial soil on the eastern bank of that stream. The sediments of the Gulf coastal plain were derived from the erosion and denudation of the old lands to the northward.

The soils of the Atlantic and Gulf coastal provinces, formed as vast outwash plains, are very diversified, due to source of material, age, and climatic conditions. They comprise a sufficient range in texture and climate to support a highly varied agriculture. There are great tracts of general farming land, besides wide areas of special-purpose soils adapted to highly specialized industries. The latter soils require refined and intensive methods of cultivation. Predominantly sandy, these soils are easy to cultivate, and they are well drained except in the lower coastal plain belt. Good aëration is usually found because of their open structural condition. Severe leaching occurs in times of heavy rainfall, for the same reason. When sufficiently supplied with organic matter, carefully fertilized, and cultivated properly, these soils support a great variety of crops, such as cotton, corn, oats, forage crops, and peanuts, besides vegetables and fruits of many varieties.

CHAPTER IV

GEOLOGICAL CLASSIFICATION OF SOILS
(CONTINUED)

Ice in the form of glaciers has been, as already stated, a very great factor in soil formation, especially in the north temperate zones of North America, Europe, and Asia. Not only was the old mantle of material swept from the land by the advance of the ice, but a new soil was laid down as drift material. This drift was sometimes merely ground-up rock, sometimes such flour mixed with the original residual soil, and sometimes glacial material wholly reworked and considerably stratified by water. Besides this, the streams of water that issued from under the glaciers were instrumental in many cases in distributing sediments a considerable number of miles southward of the ice front. Glacial lakes, also, when in existence for sufficiently long periods, furnished basins for the distribution and deposition of materials derived from the erosive and grinding power of the ice. The ice also furnished a large amount of very fine detritus, which was susceptible to wind movement. This material, reworked and deposited as bars in stream beds, was carried many miles by the prevailing westerly winds during a period of aridity following the glacial epoch. It now exists over wide areas, especially in the Middle West of the United States and in northern China, in which places it reaches its best development.

It is the important soil of these regions. Glaciation was instrumental, then, either directly or indirectly, in the formation of three general classes of materials — glacial drift soils, glacial lake soils, and a certain class of *Æolian* materials designated as loess and adobe.

34. The ice sheet.[1] — If in any region, but more likely one of some elevation, the temperature and the snowfall stand in such relationship that the heat of summer does not offset the winter accumulation of snow, great snow fields form. As this condition persists year after year, and the snow becomes deeper and more widely spread, the temperature is reduced to such an extent as to increase the proportion of the precipitation which persists through the summer's heat. The pressure of the overlying snow, and the water from the melting surface, bring about a change of the snow into ice. Often a recrystallization appears to occur without a melting and refreezing. As the depth of ice increases, the phenomenon of movement is inaugurated as the thickness of the ice at the center develops strong lateral pressure. Ice, when under great stress, exhibits a plasticity which it does not ordinarily possess. As it moves slowly forward under this tremendous pressure, and with a thickness of development almost incredible, it conforms itself to every unevenness of the surface it may be invading. It rises over hills, or shapes itself to valleys and even small depressions, with surprising ease. The rate of advance or retreat of a glacier is determined by the rate at which its edges are wasting or melting away. If the melting is slow, the ice front advances; if it just balances the advance, the

[1] For a complete discussion of glaciers and glaciation, see Salisbury, R. D. The Glacial Geology of New Jersey. Geol. Survey of New Jersey, Vol. 5. 1902.

ice front is at a standstill; but if the wasting is rapid, and the advance of the glacier is not fast enough to replace this waste, the ice is said to be retreating. A great ice sheet may exhibit all three of these conditions many times in its history.

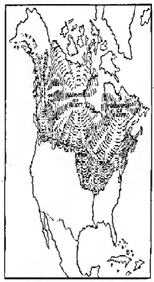

FIG. 7.—Map of North America, showing the area covered by the great ice sheets, the three centers of accumulation, and the approximate southward extension.

35. The American ice sheet. The northern part of the American continent was at one time covered by a

great sheet of ice possessing all the properties described above. Accumulation seems to have occurred in three well-defined centers, from which, over long geologic periods, the ice slowly moved southward, encroaching upon and covering thousands of square miles. The ice cap of Greenland is a very good example of the conditions then existing in the northern part of the United States. The area covered by glaciers in North America at the time of the greatest extension of the ice is estimated as 4,000,000 square miles. The thickness of the sheet was probably very great, ranging from a few feet at the margin to probably a mile or more toward the centers; at least it was thick enough to override some of the highest mountains of the New England ranges. Local glaciation also occurred on the hill and mountain tops, which tended to increase the apparent thickness of the ice mantle.

36. **Cause of the ice age.** — The ice age was not one unbroken invasion and retreat of the ice cap, but was, as is conceded by all authorities on glaciation, really divided into epochs. Five great invasions appear to affect at least the central part of the United States, possibly without bringing about a disappearance of the ice across the Canadian border. These interglacial periods are shown by forest beds, accumulations of organic matter, and evidences of erosion between the drift deposited by the successive ice sheets. Some of the interglacial periods evidently were times of warm, and even semitropical, climate. Just exactly what was the cause of the ice age is still under dispute. The most probable theory, both as to its occurrence and as to its disappearance, is that a change in the carbon dioxide content of the atmosphere took place. It is believed

that doubling the amount now present would bring about tropical climate in the temperate zones, while halving it would cause frigid conditions and a probable return of the great ice fields.

37. The extension of the ice sheet. — While the advancing ice in general exhibited well-defined viscosity, certain parts were more or less rigid. This was especially true of the parts near the edges of the sheet. These parts had become filled in their advance, particularly near the bottom, with earthy and stony material, which aided the erosive processes to a very great degree. The eroding and denuding power of the glaciers is shown everywhere by the gouged-out valleys and by the scratches, or striæ, on exposed rocks. As this sheet of ice slowly advanced a few inches or a few feet a day, the mantle of residual soil was carried away or mixed with the rock flour constantly formed by the moving ice. The original soil was really an instrument for more effective ice action. The scouring effect is observed now to the best advantage in valleys which lay longitudinally to the ice movement, as did the valleys of the Finger Lakes of central New York. Valleys lying at right angles to the ice were very often partially or wholly filled with débris, and the entire topography was altered. Rivers flowing under the ice often left large amounts of materials designated now as eskers and kames. The mixing, grinding, transporting, and stratification that went on emphasizes again the great influence of glaciation on general topography and soils.

The greatest southward extension of the ice in the United States is marked by a great terminal moraine (Fig. 8). It is supposed that the margin of the sheet was stationary at this point for a sufficiently long period to allow this

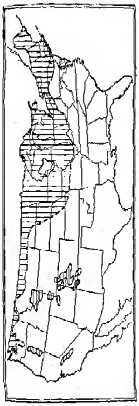

Fig. 8. — Area of the United States covered by glacial ice and the approximate location of the great terminal moraine.

narrow band of material to collect by the continual melting of the ice and a consequent dumping of its load of débris. This moraine is by no means continuous, and for miles across the continent no trace of it can be found. It extends, roughly, eastward from the Canadian border in Washington to the upper sources of the Missouri River, then down that river to St. Louis, up the Ohio River, northeastward until the southwest border of New York is reached, and then southeast to New York City and Long Island. Many other moraines are found to the northward, marking points where the ice became stationary for a time during its retreat.

33. *The ice as a soil builder.* — It was during these retreats that the ice acted as a soil-forming agent. Material gathered and ground by the ice as it pushed to the southward was finely pulverized and it is only natural to suppose that this débris was deposited as the ice slowly retreated by the melting back of its margins. The material laid down as a great mantle over the glaciated areas is called drift. Some of this has been reworked and stratified by water, but a very large proportion has remained untouched since it was laid down by the melting ice. It presents in most cases — except at the very surface, where weathering may have occurred or organic matter accumulated — exactly the same condition as when deposited. This mass of unstratified material is heterogeneous, both as to size of the particles that make it up and as to its rock composition. It may be coarse and bowldery, especially in mountains or where there are gneisses or schists, or it may be very fine where the rocks are soft. Bowlder clay is a term sometimes used in describing the matrix of this glacial deposit. In some cases foliation occurs, and often coarse and fine layers

of till may alternate. This great mantle of material, varying in thickness and constitution according to the underlying rocks and the strength of glaciation, gives a great soil province in northern United States which may be designated as glacial till soil.

39. Glacial till soils. The glacial till soils may be characterized physically as heavy or relatively heavy soils. The tremendous force of the grinding has produced fine particles, and as a consequence clay loams and silt loams predominate. Such soils usually have a subsoil which is finer than the surface material and may be so impervious to water as to produce bad drainage conditions. The individual particles of a glacial soil are found to be unweathered to a great degree unless the soil is mixed with some of the old mantle of residual material which once overspread all our glaciated areas. The particles are jagged and unrounded; the feldspars retain all of their luster, and the iron stains so common in residual soils are almost absent. As the glacial soils are young soils, their colors are seldom made up of reds and yellows, but grays and browns prevail. Red may occur, however, where red sandstones have been glaciated or where red residual soil has become incorporated in the till. Where considerable organic matter has accumulated the soil is usually very black. The subsoils in the glaciated areas usually present colors ranging from light grays to light browns. Blue or mottled clay or clay loam is often found, due to a lack of aëration in the soil; to the soil expert such a condition near the surface indicates a need of drainage.

40. Composition of glacial soils. The chemical composition of glacial soil approaches more nearly than that of any other soil the composition of the original rock.

This close resemblance to the parent rock is not surprising, since glacial soil is ground-up rock material of recent formation on which the weathering agencies have as yet had little time for action. Therefore the amounts of the important constituents in such soil are governed largely by the composition of the original rock. The lime content is due to such a relationship, and the agricultural value of the soil is greatly influenced thereby, since large amounts of calcium are of great importance to soil fertility. The hill soils of central New York (Volusia series) come from shales poor in lime, and the soil owes its properties very largely to this lack, which is traceable to the parent rock. On the other hand, certain glacial soils of the Mississippi Valley (Miami series) formed from sandstones and limestone, contain plenty of lime due to the nature of their rock origin. Glacial soils from limestone always contain plenty of lime, a condition that is far from true with residual soils.

41. **Humus of glacial soils.** — The humus content of glacial soils depends to a large extent on the climatic conditions under which the soil has existed since its formation. If environmental factors have been such as to encourage the accumulation of organic matter, these soils will exhibit the deep black color that arises from the presence of such material. If, however, conditions do not encourage the natural growth of a heavy vegetation, the amount of organic matter in such virgin soil will be low. Lime may be a very great factor in such soils, not only in the encouragement of plant growth, but also in the proper decay of the plant tissue after it has become incorporated with the soil.

Glacial till soils are found distributed over all the area north of the great terminal moraine, and stretch, roughly,

from New England to the Pacific coast (see Fig. 4). They comprise a great variety of soils, not only as to their physical character, but also as to fertility. They are adapted to many crops, but general farming is practiced on them to the greatest degree. This means extensive, rather than intensive, operations. In some localities dairying has been developed to a large extent, and has proved to be not only a means of obtaining paying returns from such soils, but at the same time a method of keeping up their fertility.

45. Glacial lakes.—Such great masses of ice could not advance and retreat, again and again, on such an extensive scale, without causing the formation of great torrents of water. It is more than probable that at all times great streams gushed from the ice front, laden with much sediment. Often these streams were under pressure, which when released caused an immediate deposition of material. As long as the ice front stood south of the east and west divide, this water found ready egress and flowed rapidly away to deposit its load as gravelly outwash, river terraces, valley trains, and alluvial fans. These formed alluvial soils of varied character, depending on the size of the materials carried. There came a time, however, in the retreat of the ice, when the front stood north of the divide and only a small proportion of the water found itself free to flow over the divide and away to the southward. The remaining water was ponded between the ice front and the old divide. Thus glacial lakes were produced, of large or small extent, according to the position of the ice. The location of such lakes is shown on the soil map of the United States. The ponded water remained in this condition for many years, subject, of course, to changes concordant with

the oscillation of the ice front. With the ice melting rapidly on the hilltops, these lakes were constantly fed by torrents from above which were laden with sediment derived not only from under the ice, but also from the unconsolidated till sheet over which it flowed. As a consequence, there were in the glacial lakes deposits ranging from coarse delta materials near the shore to fine silts and clay in the deeper and stiller water. Such materials now cover large areas (see Fig. 4), not only in New York State and along the Great Lakes, but also in the Red River Valley and in the northerly inclined valleys of the Rocky Mountains and the Cascade and Sierra Nevadas. They make up by far the most important lacustrine soils.

43. Lacustrine soils — glacial lake. — Glacial lake soils probably present as wide a variation in physical characteristics as any of our great soil provinces. Being deposited by water, they have been subject to much sorting and stratification, and range from coarse gravels on the one hand to fine clays on the other. They are generally found as the lowland soils in any region, although they may occur well up on the hillsides if the shores of the old lakes encroached thus far. The color of such soils varies from gray to black, according to the degree of organic matter present. The humus content of such soils, as with the glacial till, varies with climate, and may be high, low, or medium according to conditions. The thickness of glacial lake deposits is variable, ranging from a few feet to many feet. In chemical composition they closely approximate the soil from which they are derived. This is particularly true as regards the presence of lime. The Dunkirk soil of southern New York, a wash from the lime-poor

Volusia series of the highlands, is low in lime; while the same soil just south of Lake Ontario, obtaining its wash from a limestone till (Ontario series), is rich in lime. As may be inferred from the above comparison, the glacial lake soils of the United States are variable in their fertility.

The distribution of the glacial lake deposits, as seen from the soil map of the United States, is fairly wide. Such soils are found in areas large enough to be of great agricultural influence, extending from New England westward along the Great Lakes until their greatest expanse is reached in the Red River Valley. These deposits make up some of the most important soils of the northern states. They are valuable not only for extensive cropping with grain and hay, but also for fruit and trucking crops. The Ice Age was certainly not in vain as far as the production of fertile soils is concerned.

44. Lacustrine soils — recent lake. — There is yet another lacustrine soil to be considered besides the one just discussed — recent lake soil. While the glacial lake deposits were formed many thousands of years ago, the lake soils of the second group are in process of construction. It is a well-known fact in physical geography that lakes are only enlarged stream beds, and are doomed ultimately to be filled by river sediments. Such soils have been reclaimed to a certain extent, but their acreage is not large enough to give them the importance of the glacial lake soils. The lake soil is usually of a fine character, rich in humus, of good tilth. If properly drained, it is almost invariably highly productive, and is adapted to a variety of crops depending on climatic conditions.

45. Æolian soils. — During glaciation much fine material was carried miles below the front of the glaciers by streams that found their sources therein. This fine sediment was deposited over wide areas by the overloaded rivers. The accumulations occurred below the ice front at all points, but seem to have reached their greatest development in what is now the Missouri Valley. There, too, the sediment seemed finest, and, coming mainly from glaciated limestones, was very rich in calcium. It is generally agreed by glacialists that a period of aridity, at least as far as this particular region is concerned, immediately followed the retreat of the ice. The low rainfall of this period was accompanied by strong westerly winds. These winds, active perhaps through centuries, were instrumental in the picking-up and distributing of this fine material over wide areas of the Mississippi, Ohio, and Missouri valleys. One strong argument for this Æolian origin is that the soil is found in its *deepest and most characteristic development* along the eastern banks of the large streams. Especially noticeable is the extension down the eastern side of the Mississippi River almost to the Gulf of Mexico. This wind-blown material, called loess, is found over wide areas in the United States, in most cases covering the original till mantle. It covers eastern Nebraska and Kansas, southern and central Iowa and Illinois, northern Missouri, and parts of Ohio and Indiana, besides a wide band, as already noted, extending southward along the eastern border of the Mississippi River. Due to its mode of origin, its depth is always greatest near the streams and gradually becomes less farther inland. In places, notably along the Missouri and Mississippi rivers, its accumulation has given rise to great bluffs which

bestow a characteristic topography to that region. The loess soil is found also covering the great areas of China and Siberia, and thus it is one of the important soils of the world. Another soil, made up, at least partially, of wind-blown material and found in Arizona and New Mexico, is called adobe. Volcanic soils of the western United States and elsewhere are to some extent of wind origin. Sand dunes are of Æolian origin, but these sink into insignificance as to agricultural value when compared with the soils named above, especially loess.

46. Loess soils. — Loess is usually a fine calcareous silt or clay, of a yellowish or yellowish buff color. While it may be readily pulverized when subjected to cultivation, it possesses remarkable tenacity in resisting ordinary weathering. The vertical walls and escarpments formed by this soil show one of its striking physical characteristics. In China[1] caves that house thousands of persons are dug in the defiles and cañons existing in this deposit. Another feature of loess is the presence of minute vertical canals lined with a deposit of calcium carbonate. These canals are supposed to give the soil its vertical cleavage and its tenacity. The particles of loess are usually unweathered and angular. Quartz seems to predominate, but large quantities of feldspar, mica, hornblende, augite, calcite, and other substances are found.

A few typical analyses[2] are given below.

[1] Richthofen, F. Chinese Loess. Geol. Mag., May, 1882, p. 293.

[2] Clark, F. W. The Data of Geochemistry. U. S. Geol. Survey, Bul. 491, p. 486. 1911.

A. From near Dubuque, Iowa.
B. From Vicksburg, Mississippi.
C. From Kansas City, Missouri.
D. From Cheyenne, Wyoming.

	A	B	C	D
SiO_2	73.08	60.69	74.46	67.10
Al_2O_3	12.00	7.95	12.26	10.26
Fe_2O_3	2.63	2.61	3.30	2.52
MgO	1.13	4.56	1.12	1.34
CaO	1.50	8.95	1.60	5.88
Na_2O	1.68	1.17	1.43	1.42
K_2O	2.13	1.08	1.83	2.08
P_2O_5	.23	.13	.09	.11
CO_2	.29	9.84	.49	3.07
H_2O	2.50	1.14	2.70	5.09

It is immediately noticeable that the lime content of these soils is high, as is also the phosphoric acid. In fact, all the more soluble constituents are present in relatively large quantities, as would naturally be expected from the mode of origin of such soils — they having been subjected to aridity and then deposited by the wind at a relatively recent period. It is maintained by some geologists[1] that the deposition of loess is still going on in certain parts of the world, but that the rate of accumulation is so exceedingly slow that it escapes the notice of all but trained observers. The lack of fossils, particularly those of plants, is accounted for by this slow rate of formation, which allows sufficient time for all organic matter to become fully oxidized before being covered by the drifting material. Snail shells are often found, but as they are of land species they argue against a water origin of loess.

[1] Merzbacher, G. The Question of the Origin of Loess. Mitt. Justus Perthes' Geogr. Anst., 59, pp. 10-18, 69-74, and 126-130. 1913.

47. Distribution of loess. — Not only is loess found over thousands of square miles in the central part of the United States, but it occurs elsewhere in large areas. It is greatly developed in northern France and Belgium, and along the Rhine in Germany, where it is an important soil in all the valleys that are tributary to that river. Silesia, Poland, southern Russia, Bohemia, Hungary, and Roumania, all have deposits of this highly fertile material. In Europe it extends from sea level to elevations of 5000 feet, showing its independence of water as a formative agent. In China it is found over a very large part of the valley of the Hoangho, a region probably larger in area than France and Germany combined. The thickness of the deposit is variable, ranging from a few feet to several thousand feet in certain places. The depth is practically always sufficient for any form of agricultural operations.

Wherever moisture relations are favorable loess is an exceedingly fertile soil, due to its rich stores of potash, phosphorus, and lime. Its organic content is usually medium to high, depending on conditions. In general it may be classified as the richest soil in the world, considering its wide extension and the great variety of climate and of crops to which it is subjected. In the United States it occurs in the Corn Belt region, and might be called the great corn soil of the Mississippi Valley.

48. Adobe soils. — The term adobe is a name applied to a fine calcareous clay or silt formed in a manner somewhat like that in which loess is formed. It is supposed that, while part of the deposit came from the waste of talus slopes as mountains were weathered under conditions of aridity, the remainder had an origin similar to that of

loess.[1] Certain characteristics also seem to indicate that the valley adobe might have been deposited by water.[2] It appears, therefore, that, while the physical characters of all adobe are somewhat similar, its mode of origin and chemical composition may be variable. Below are the analyses[3] of two typical adobe soils: —

	A	B
SiO_2	66.69	64.64
Al_2O_3	14.16	13.19
Fe_2O_3	4.78	5.12
CaO	2.49	13.91
MgO	1.28	2.96
K_2O	1.21	1.71
Na_2O	.67	.50
CO_2	.77	8.55
P_2O_5	.20	.94
Organic matter	3.00	3.42

Like the loess, adobe is an exceedingly rich soil, but it occurs in an arid or a semiarid region. When irrigated, its fertility seems inexhaustible. It is found in Colorado, Utah, southern California, Arizona, New Mexico, and Texas. It has an especially wide distribution in New Mexico. Like loess its elevation is variable, ranging from sea level in California and Arizona to 6000 feet along the eastern border of the Rocky Mountains. Its maximum thickness cannot be estimated, as it is very

[1] Russell, I. C. Subaërial Deposits of the Arid Region of North America. Geol. Mag., August, 1889, pp. 342–350.

[2] Hilgard, E. W. Relation of Soil to Climate. U. S. Weather Bur. Bul. 3. 1892.

[3] Merrill, G. P. Rocks, Rock Weathering, and Soils, p. 321. New York. 1906.

little eroded and is supposed to be still accumulating. Some valleys are known to be filled to a depth of 3000 feet with this material. Its characteristics are its fine texture, its great depth, its wide distribution, and its great fertility when moisture conditions are suitable for crop growth.

49. Sand dunes. Sand dunes are the outgrowth of two conditions — a large quantity of sand and a wind that blows in a more or less prevailing direction. Under such conditions the sand and other fine material not only is blown into heaps, but also tends to move in the direction of the prevailing wind. Such heaps or mounds of sand may travel several feet a day by the continual movement of the sand grains up the windward side of the dune, only to be deposited again on the leeward side. Sand dunes may often assume gigantic proportions, being sometimes several hundred feet high and twenty or thirty miles long. In such proportions they become a grave menace to agriculture, not only because they are an absolutely valueless medium for plant growth, but also because they cover fertile lands and entirely blot out all plant growth. The particles of this wind-blown sand are usually round, from the continual abrasion that they receive. A great many minerals may be represented, but quartz is the commonest, especially if the dune originally had its origin on a lake or a seashore.

50. Volcanic dust. — From early geologic times deposits of the very fine material that is continually being ejected from volcanoes have been distributed over the earth's surface. These deposits are usually flour-like, and while at one time they probably covered many square miles of territory, they have succumbed very

largely to erosion and denudation, and only remnants are found at the present time. Such material may be found in Montana, Nebraska, and Kansas. Æolian deposits of this character are usually rather porous and light, and are likely to be highly siliceous. They are not of great agricultural importance.

CHAPTER V

CLIMATIC AND GEOCHEMICAL RELATIONSHIPS OF SOILS

ALTHOUGH during the process of weathering the tendency of all soil is toward a common composition, such a condition is never reached, due to different kinds and varying intensities of decay and disintegration. Soils lend themselves readily to a geological classification because of this difference in mode of formation. Such a classification really signifies a variation in composition. A difference in age, a preponderance of physical agencies over chemical or vice versa, a difference in the transportive agencies, or a variation in climatic conditions after a soil is once formed, will assuredly give a different product, not only chemically, but physically and biologically as well.

51. **Climatic relationships.** It is evident that climate is a factor in all geochemical relationships of soils. Not only does climate determine the kind of weathering and its intensity, but in many ways it influences very largely the characteristics of the soils of different provinces and sections. Climate must be considered also in the geological classification of soils, since it plays such an important rôle in determining the kind and intensity of the formative agents. In any scheme of grouping for the systematic survey and mapping of soils, climate is the very first factor to be considered. It gives three great groups — tropical, subtropical, and temperate. These may in turn be subdivided into arid, semiarid, and humid.

In the utilization of soil, climate, particularly as regards rainfall and temperature, plays an important part. Crop adaptation is really more of an adaptation to climate than to soil, although the latter also should be very carefully studied. The climatic relationships in soil formation, in soil chemistry, and in geochemistry in general, cannot be too strongly emphasized, whether the viewpoint be technical, practical, or merely educational.

52. Geochemical relationships of residual and marine soils. — It is evident from the above that coastal plain, residual, and glacial soils should exhibit certain well-defined general differences due to their mode of formation. The following analyses, which are representative of the provinces in question, illustrate the chemical differences of coastal plain and residual soils: —

Analyses of Typical Coastal Plain and Residual Soils

	Light Sandy Loam from Maryland, Average of 3 Samples[1]	Cork and Windy Clay Loam Soil, Average of 3 Samples[1]	Residual Soil from Granitic Gneiss[2]	Residual Soil from Virginia Limestone[3]
SiO_2	92.50	80.55	45.31	57.57
Al_2O_3	3.20	8.82	26.55	20.44
Fe_2O_3	.91	2.67	12.18	7.93
P_2O_5	.05	.42	.47	.10
CaO	.41	.47	trace	.51
CO_2	.08	.05	trace	.28
MgO	.35	.30	.40	1.30
Na_2O	.50	.49	.22	.20
K_2O	.70	1.22	1.10	4.91

[1] Veitch, F. P. The Chemical Composition of Maryland Soils. Maryland Agr. Exp. Sta., Bul. 70, pp. 71 and 73. 1901.

[2] Merrill, G. P. Weathering of Micaceous Gneiss in Albemarle County, Virginia. Bul. Geol. Soc. Amer., Vol. 8, p. 160. 1897.

[3] Diller, J. S. The Educational Series of Rock Specimens. U. S. Geol. Survey, Bul. 150, p. 385. 1898.

It is to be noted, in the first place, that silica exists in large quantities in the coastal plain soils, due to the fact that quartz is such a resistant mineral. The constant washing that this soil has undergone has very largely decomposed the silicates. The aluminum and iron are rather low on the average in such soils, even in those of the richer type. It is to be noted also that the amounts of phosphoric acid, calcium, potash, magnesia, and sodium are much less in the marine soils, due to the excessive washing that they have received. These figures would lead to the belief that in general the marine soils are lower in the mineral plant-food constituents than soils formed *in situ*. The amount of organic matter that they may contain depends entirely on their location and climatic conditions. They may or may not be rich in humus, according to circumstances. It is generally considered, however, that they are not so well supplied with the organic elements as are other soils.

43. **Residual and glacial soils.** — A comparison of residual and glacial provinces cannot be made with such assurance, because of the many kinds of rocks that may have been parent to the soils and because of the great variety of climatic conditions under which the soil-forming processes may have gone on. Such a comparison is best made in a region where both residual and glacial soils are found, as nearly as it is possible to judge, coming from the same rocks. Analyses of soils under such conditions are available, from the driftless and glaciated parts of Wisconsin. The original rock was limestone. The analyses[1] are as follows: —

[1] Chamberlin, T. C., and Salisbury, R. D. The Driftless Area of the Upper Mississippi. Sixth Ann. Rept., U. S. Geol. Survey, pp. 249-250. 1885.

Analyses of Residual and Glacial Clays from the Driftless and Glaciated Areas of Wisconsin

	Residual		Glacial	
	1	2	3	4
SiO_2	71.13	40.13	40.22	48.87
Al_2O_3	12.40	21.08	8.47	7.54
Fe_2O_3	5.52	11.04	2.83	3.53
MgO	.38	1.93	7.80	7.95
CaO	.85	1.22	15.65	11.83
Na_2O	2.19	1.33	.84	.92
K_2O	1.61	1.81	2.30	2.60
P_2O_5	.02	.04	.05	.13
CO_2	.43	.39	18.76	15.47
H_2O	4.63	11.72	1.05	2.03

These analyses illustrate to very good advantage the beliefs entertained by Chamberlain and Salisbury regarding the differences between residual and glacial clays. Residual clay is designated by them as "rock rot," and glacial clay as "rock flour." The latter, being less weathered, retains a larger proportion of its easily soluble materials. It is to be noted here, as in the comparison of marine and residual soils, that silica, aluminium, and iron are lower in the soil subjected to the less amount of leaching, which in this case is the glacial clay. This in itself would serve to indicate that the important plant-food constituents are generally present in larger quantities in the glacial clay. In fact, it would be expected that the glacial soils would approximate very closely the rock or rocks from which they came. The phosphoric acid, lime, sodium, magnesium, and potash of the residual soils in this case amount on the average to 5.73 per cent, while that of the glacial clays reaches the high figure of 24.01 per cent. This is due largely to the great amount

of lime present, and again emphasizes the point that, while a glacial soil from a limestone is rich in lime, a residual soil from the same rock is usually poor in that constituent. Even loess, which has been subjected to some washing before being deposited, is a considerably richer soil than those of residual origin.

It must be remembered, however, that these comparisons are of a general character and do not apply to all cases, since many glacial soils may be very much poorer in the plant-food constituents than some of the representative residual soils. Moreover, the physical condition of a soil is a great factor in productivity. As a matter of fact, the mere presence of plant-food is but one of a considerable number of factors that determine the crop-producing power of a soil. Also, the humus content of the soils of various provinces may be variable, due to climatic conditions. Neither are all glacial soils rich in lime, as that constituent is determined largely by the amount in the parent minerals. A rock poor in lime, therefore, must from necessity give rise, when glaciated, to a soil deficient in lime. This is well illustrated by the average analyses[1] of the loam soils of Ashtabula County, Ohio, originating from the glaciation of the lime-poor shales of that region:—

CaO	.25
MgO	.61
P_2O_5	.06
K_2O	1.87
N	.15
Humus	1.70

[1] Ames, J. W., and Gaither, E. W. Soil Investigations. Ohio Agr. Exp. Sta., Bul. 261. 1913.

However, our major premise does seem to stand in a general way — that a glacial soil, other things being equal, contains a larger amount of the mineral plant-food constituents, and ordinarily a smaller amount of such materials as silica, iron, and aluminum, than does a corresponding soil of residual origin.

The following data[1] bring out the points already dealt with in their fullest significance:

PERCENTAGE OF P_2O_5, CaO, MgO, AND K_2O IN SOILS OF DIFFERENT PROVINCES

Soils	P_2O_5	CaO	MgO	K_2O	Total
7 Coastal plain . . .	.07	.24	.36	.70	1.37
3 Residual (crystalline) .	.25	.67	.75	2.08	3.75
10 Glacial	.22	1.38	.49	2.08	4.15

64. **Effect of glaciation on agriculture.** — These differences between residual and glacial soils reflect on the general fertility of the soils. In a comparison of the driftless area of Wisconsin with the glaciated parts,[2] only 43 per cent of the former is improved as against 84 per cent of the latter, while the value of the farms on the glaciated soil averages 50 per cent higher. The same general differences appear between the glacial and residual soils of Indiana[3] and Ohio.[4]

[1] Failyer, G. H., and others. The Mineral Composition of Soil Particles. U. S. D. A., Bur. Soils, Bul. 54. 1908.
[2] Whitbeck, R. H. The Glaciated and Driftless Portions of Wisconsin. Bul. Geog. Soc. Phil., Vol. IX, No. 3, pp. 10-20. 1911.
[3] Von Engeln, O. D. Effects of Continental Glaciation on Agriculture. Bul. Amer. Geog. Soc., Vol. XLVI, p. 246. 1914.
[4] Ames, J. W., and Gaither, E. W. Soil Investigations. Ohio Agr. Exp. Sta., Bul. 261. 1913.

Von Engeln,[1] in a comparison of glaciated soils with corresponding residual areas, was able to point out certain general differences. The agricultural condition within the zone of glaciation was always consistently higher than that beyond the regions of drift accumulation. The extensive leveling due to glacial erosion and deposition had almost always resulted favorably for agricultural operations. Even the thickness of the drift was found to conserve the ground water supply. Not only did this author conclude that glacial soils were richer in soluble plant-food constituents than residual soils, but he also showed that glacial soils had a greater crop-producing power and a higher agricultural value. The dominant *textural quality of glacial soils* seems adapted to certain staple food crops, and, due to their intermingling, a considerable opportunity for diversified and intensified farming is offered. It is therefore evident that in any study of soils, particularly those of the United States, a careful consideration of the effects of glaciation is necessary. The great ice sheet has been responsible in some cases for the rejuvenation of our soils, in others for the production of an entirely new soil mantle. Even the alterations in topography are factors not to be ignored.

53. Arid and humid soils.[2] — This distinction between soils due to differences in the formative process is always evident, but is particularly striking in a comparison of arid and humid regions. In areas of light rainfall the physical agents are dominant, and disintegration goes on very largely without decomposition. Under humid conditions,

[1] Von Engeln, O. D. Effects of Continental Glaciation on Agriculture. Bul. Amer. Geog. Soc., Vol. XLVI, pp. 353-355. 1914.

[2] For a more complete discussion of this subject, see Hilgard, E. W. Soils, Chapters XX and XXI. New York. 1911.

however, the chemical forces are the determining factor as to the character of the soil. Arid soils are therefore usually coarser soils and their color is very likely to be light. Such soils are deep and uniform, there being but little difference between the surface and the subsoil. The soils of the humid regions are usually of fine texture, particularly in residual regions, since the chemical agencies have been so active. Various colors may develop because of oxidation, hydration, and the presence of organic matter. Such soils usually are not excessively deep, and are likely to be underlaid by subsoils heavier than the surface. The general physical condition and tilth of arid soil is uniformly better than that of regions of plentiful rainfall.

Chemically, because of less leaching the arid soils contain more of the important mineral plant-food elements. The following analyses bring out the differences in a striking manner: —

	Arid Soils Average of 573 Samples[1]	Humid Soils Average of 696 Samples[1]	Average Composition of Lithosphere[2]
Insoluble residue and soluble SiO_2	75.87	88.21	59.38 (SiO_2)
Al_2O_3	7.21	3.66	15.81
Fe_2O_3	5.48	3.88	6.34
P_2O_5	.16	.12	.29
CaO	1.43	.13	4.78
MgO	1.27	.29	3.74
Na_2O	.35	.14	3.25
K_2O	.67	.21	2.98
Water and ignition	5.15	4.40	—
Humus	1.13	1.22	—

[1] Hilgard, E. W. The Relation of Soil to Climate. U. S. Weather Bur., Bul. 3. 1892.

[2] Clarke, F. W. Data of Geochemistry. U. S. Geol. Survey, Bul. 491, p. 33. 1911.

It is immediately apparent that the arid soil is poorer in silica than the humid soil, but richer in iron and aluminium, indicating a less weathered condition of the feldspars. Due to a greater amount of leaching, the humid soil is much lower in phosphoric acid, lime, magnesium, sodium, and potassium. The humus in arid soils is somewhat lower than in the soils under better conditions of rainfall, as one would naturally expect. The amount of easily soluble material is higher in arid regions, due to the lack of heavy rain and the tendency for soluble salts to accumulate. A comparison of the analyses above with Clarke's estimate regarding the composition of the earth shows that the humid-region soil has moved farther away from the average soil-forming rock than the soil produced under conditions of aridity.

Biologically, organisms are found active at greater depths[1] in arid regions than in humid regions, because of the loose structure of arid soils and because of their good aëration. Such soils are seldom water-logged. In humid regions bacterial action is limited very largely to the surface foot of soil, since only there are the aëration and the food conditions adequate. The intensity of biological activity in arid soils is very largely governed by moisture, and when moisture conditions are satisfied bacterial changes may be expected to take place rapidly. Cases are on record in which the soluble salts due to bacterial action have become of such concentration as to be toxic to plants.

56. Soil color. — Another characteristic of soil is its color, which has originated during the processes of soil

[1] Lipman, C. B. The Distribution and Activities of Bacteria in Soils of the Arid Region. Univ. of Calif., Pub. in Agr. Sci., Vol. 1, No. 1, pp. 1–21. 1912.

formation, largely through natural weathering agencies. This is really a phase of geochemistry, particularly as regards those tints that originate from the oxidation of the iron. Color has long occupied the attention of geologists and agriculturists, in the first place because it gives a clew to the mode of soil formation, and in the second place because it is to a certain extent an index to agricultural value. At the outset it must be understood that soil colors are not pure colors, although spoken of as such, but tints and shades. In soils it is possible to find almost any conceivable color, ranging from white sands to black swamp mucks or the blood-red clays of the Piedmont region. The three coloring matters of soil may be classified as (1) the color arising from the mineral, (2) the color given by the humus present in the soil and around the particles, and (3) the reds or the yellows due to oxidization of the iron. These three primary, or basal, colors may be represented for convenience as follows:—

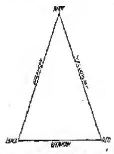

FIG. 9.—A triangular representation of the three primary soil colors and their mixtures.

A soil low in humus, and with the iron either absent or unoxidized, will be of a light color. Sea sands are good illustrations of this condition. A well-drained soil containing large quantities of organic matter will present a deep black color in spite of the oxidized iron, as the latter will be masked to a large extent. If humus is low or lacking and the iron is oxidized, a red or a yellow color may characterize the soil. As might be expected, there are blendings of these three primary colors, and grays, browns, and yellows of varying intensities are common.

57. White and black soils. — The light colors in soils are not due to the agencies of weathering, but rather to a lack of such action. The cause of such coloration is therefore not hard to explain. The development of the black or dark colors and tints, being due to the accumulation of organic matter, indicates the operation of two favoring conditions: first, climatic agencies that stimulate the luxuriant development of plants; and, secondly, sufficient aeration to promote a favorable decay of such tissue. It is a well-recognized fact that in order to develop a black color from decaying vegetable matter, fairly good aëration must be provided. If such a condition does not prevail, the decayed material has a lighter hue and may exhibit toxic properties which will check or inhibit plant growth. The development of the black color, therefore, in a normal well-drained soil, is an indication of good soil sanitation.

58. Red and yellow soils. — The presence of iron, as already noted, is a very important factor in rock weathering, and the discoloration due to its presence is an unfailing indication of chemical decay. The iron in minerals occurs usually as ferrous oxide, which is soluble, especially if the water circulating among the rock fragments carries

carbon dioxide. As this water comes in contact with the air, its excess of carbon dioxide is discharged and the oxides and carbonates of iron are deposited. Under this condition oxidation goes on rapidly, and the iron passes to the ferric state and becomes insoluble. Thus it may be seen that iron imparts a fatal weakness to rocks and minerals in which it may exist, due to its solubility; yet from the oxidation that it undergoes, it tends to persist and accumulate in soils. A corollary might be added to the law of mineral resistance, to the effect that "the more iron a mineral contains, the more susceptible it is to the weathering agencies."

Therefore, from the geochemical standpoint, the development of the red and yellow colors in soils has been the subject of considerable dispute from time to time. The red and yellow soils of the Cotton States frequently excite comment, especially as a difference in fertility is popularly recognized, the red surface soil with a red subsoil being considered more fertile than a similar soil with a yellow subsoil. Crosby[1] believes that the difference in color is due to a difference in hydration of the iron oxides. The soil temperatures, particularly in tropical and subtropical regions, have first tended to fully oxidize and hydrate the iron, and then to dehydrate the soil at the surface into the deep red color, leaving the subsoil yellow and causing the contrasts so markedly evident. The ultimate product of both oxidation and hydration would be limonite, a yellow mineral; while if only oxidation were active, hematite, which imparts a red color, would result as a final product. A dehydration of the limonite would cause the formation of hematite

[1] Crosby, W. O. Colors of Soils. Proc. Boston Soc. Nat. Hist., Vol. 23, pp. 219-222. 1878.

or some intermediate product. The composition of the common iron oxides found in soils tends to support Crosby's explanation: —

Hematite	Fe_2O_3	Red
Turgite.	$2\ Fe_2O_3 . H_2O$	
Goethite	$Fe_2O_3 . H_2O$	
Limonite	$2\ Fe_2O_3 . 3\ H_2O$	
Xanthosiderite . .	$Fe_2O_3 . 2\ H_2O$	
Limnite	$Fe_2O_3 . 3\ H_2O$	Yellow

Merrill[1] holds the same idea, but thinks that the surface soil may contain relatively more iron than the subsoil. He considers that the ferric iron oxides, because of their insoluble nature, tend to accumulate at the surface, and because of their large quantities and because they are there subjected to more vigorous weathering action the vivid red colors tend to develop.

The iron coloring matter usually exists as a coating[2] on the soil particles, although it may sometimes occur as concretions. It is found also that in general, but not always, the intensity of the color varies with the amount of iron present. From a large number of analyses compiled by Robinson and McCaughey,[3] the following figures may be obtained showing the authority for such a statement: —

Average Iron Content of Soils	Percent of Ferric Iron
Deep reds to light reds	14.18
Ochre yellow to yellow	8.85

[1] Merrill, G. P. Rocks, Rock Weathering, and Soils, p. 375. New York. 1906.

[2] Van Bemmelen, J. M. Beiträge zur Kenntnis der Verwitterungsprodukte der Silikate in Ton-, Vulkanischen-, und Laterite-Boden. Zeit. Anorg. Chem., Bd. 42, Seite 290–298. 1904.

[3] Robinson, W. O., and McCaughey, W. J. The Color of Soils. U. S. D. A., Bur. Soils, Bul. 79, p. 31. 1911.

This being true, the thicker the film, the greater is the intensity of the color. The same quantity of iron, therefore, would make a greater showing in a sandy soil than in clay, as the amount of internal surface of the former is comparatively low and the film of iron oxide would therefore be thicker.

It is evident from the data already presented that the intensity of color arising from iron in the soil is due to several conditions. Without a doubt the oxidation that occurs is of primary importance, but the hydration that very often takes place is a powerful modifying agent. The thickness of the film, as determined by the amount of iron present or by the texture of the soil, is probably a factor having to do particularly with the intensity of the coloration, although the color or tint itself may be modified to a certain extent thereby.

59. **Agricultural significance of color.** — The white or the black color of a soil indicates the lack or the presence of an important constituent, namely, organic matter. This matter not only tends to keep the soil in good physical condition, but also acts both as a plant-food and as a source of energy for bacteria and other soil organisms. A dark soil, provided its drainage and climatic conditions are favorable, is usually a rich soil. The dark color is no mean factor in temperature relationships, since not only does a dark soil absorb heat faster than a light soil, but the tendency of the former toward reflection and radiation is much restricted. This is important with crops which must go into the soil early in the season, or which need to be pushed rapidly to maturity. A dark color, with virgin soils especially, is an excellent guide to fertility and general agricultural value.

Red colors in soil often show low or medium organic content. Besides this, the presence of oxidized iron is always an indication of age. The residual soils of the Piedmont Plateau are especially characterized in this way. Age gives opportunities for leaching, and consequently a lack of the soluble bases may be expected in such soils. The reds and the yellows are characteristic of residual soils, or of soils that have arisen from them by erosion or glaciation. A red color is almost as efficient in the absorption of heat as is black; so that the early-growth and quick-maturing tendencies of crops on a red soil, other things being equal, are about the same as on a dark soil. Hilgard,[1] who lays great stress on the agricultural significance of color, considers the mottled yellows and reds as indications of poor drainage, since such a condition shows that oxidation has been both unequal and insufficient. A soil that has a heavy blue or mottled blue clay as a subsoil will in most cases be greatly benefited by some form of drainage.

60. Soil and subsoil. —A common distinction is made between the surface soil and that which is some distance below the surface. This is natural, as the forces of soil formation have served to bring about certain distinctions, especially in humid regions, which are of importance in any consideration of soil fertility and crop growth. Climatic agencies acting on soil after it has been formed have served to intensify these distinctions. The term soil is used to designate the top layer of earth, which usually extends to the plow line or even deeper. The soil below is spoken of as the subsoil, and may be rather variable in its depth (Fig. 10). Often the subsoil is divided into the upper

[1] Hilgard, E. W. Soils, pp. 283-285. New York, 1906.

and the lower subsoil, the upper subsoil being considered to extend to about the depth of three feet below the surface. Usually, especially in humid regions, there is a

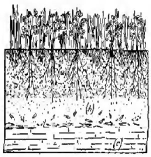

Fig. 10.—Soil and subsoil. (a), Surface soil with many plant roots; (b), subsoil; (c), country rock.

sharp line of demarcation between the soil and the subsoil, due to differences in the humus content. As organic matter accumulates faster at the surface, the soil there tends to assume a darker color. Whether the land has been tilled or not, this line of separation is fairly marked and can usually be located with little difficulty. On tilled land, where the surface soil extends to about the depth of plowing, the plow line marks the separation of surface and subsoil. Where soil samples are being taken for soil survey or soil analysis, some arbitrary depth, depending on circumstances, is usually established for the surface soil. This depth varies from six to twelve inches.

61. Soil and subsoil of humid regions. In humid cli

mates there are usually certain well-defined differences between the surface soil and the subsoil, besides the organic content already spoken of. The subsoil is usually of a finer and heavier character than the surface soil, due to the downward movement of the small particles. This tends to give the subsoil high retentive power, and may make it rather impervious to water. Poor drainage conditions may result. A certain amount of retentive power in a subsoil is of considerable advantage, in that it aids in the storage of water and prevents the excessive leaching away of soluble plant-food. Moreover, almost all the bacterial activities so important in the simplification of compounds carrying food constituents are restricted to the surface soil. The subsoil, being protected by the layers above, has not been subjected to such vigorous weathering, and as a consequence its mineral constituents are not so available for the use of the crop. The deepening of the plow line and a consequent turning-up of the subsoil must be carried out very cautiously for the above reason. The cropping power of a soil may be markedly reduced by the presence of too much of such material on the surface at one time.

The root distribution is restricted largely to the surface soil, and this condition determines to some extent the larger accumulation of humus therein and also its better aëration and drainage. Experiments conducted in Utah[1] show that with barley, corn, and clover, from 90 to 96 per cent of the roots grow in the upper seven inches of soil. From experiments made in Kansas[2] and in North

[1] Sanborn, J. W. Roots of Farm Crops. Utah Agr. Exp. Sta., Bul. 33. 1894.

[2] Ten Eyck, A. M. The Roots of Plants. Kansas Agr. Exp. Sta., Bul. 127. 1904.

Dakota,[1] the roots of such crops as alfalfa were found to penetrate to a depth of ten feet, while the small grains often showed an extension of their roots to four feet below the surface. It must be borne in mind, however, that, while some plant roots may penetrate far into the subsoil, the main feeding rootlets are restricted largely to the surface soil. This is natural, as there they find the aëration and drainage essential to normal growth. Hilgard[2] has shown that plants in arid regions have a root extension far beyond that of the same crops under humid conditions. The physical conditions of the arid subsoil, the larger amount of plant-food, and the better aeration, account for such differences.

68. **Soil and subsoil of arid regions.** — The subsoils in arid or semiarid regions do not exhibit such marked contrast to the surface soil as are observed in humid climates. In arid soils there is generally no sharp line of demarcation between soil and subsoil, the latter being as high in humus and in agricultural value as the former. Nor is any great textural variation to be observed. The latter condition is due to the fact that physical weathering is dominant in such a region. As a consequence, arid soils may be leveled, often excessively, in establishing an even surface for the application of irrigation water, without any danger of lowering the fertility thereby. Such a practice in humid regions would be fatal to the further growing of successful crops, at least for a considerable period of years.

[1] Shepperd, J. H. Root Systems of Field Crops. N. Dak. Agr. Exp. Sta., Bul. 64. 1905.

[2] Hilgard, E. W. Soils, Chapter X, pp. 161–187. New York. 1911.

CHAPTER VI

THE SOIL PARTICLE

The soil formed by the grinding-up of rocks and the intermixing therewith of small quantities of organic matter must be studied physically from the standpoint of its particles. These particles, varying in size from coarse gravel easily discernible by the naked eye to particles so fine as to be invisible under the ultramicroscope, determine very largely the different relationships of the soil to the plant. The movement of air in the soil, the circulation of water, the rate of oxidation and hydration, and the presence and virility of various organisms, are determined very largely by the size of the particles making up the soil. *Texture* is the term used to express this size of particle. Thus a soil texture may be coarse, medium, or fine, indicating that the particles making up that soil conform in general to such description. Texture is of great importance in soil study and utilization.

There is hardly any condition exhibited by the soil that is not influenced, if not directly determined, by the size of the soil particles. A study of plant conditions, whether physical or chemical, ultimately leads either directly or indirectly to a consideration of soil texture. Texture, however, is an element which can be but little modified under normal conditions. We have seen how a rock can be disintegrated and decomposed into a soil. A change in texture has been wrought, but such a process demands geologic ages for its fulfillment. In the time

covered by the life of man the necessary forces are not active enough to have this effect; consequently, as far as the farmer is concerned the texture of the soil in his field is subject to but slight alteration. A sand remains a sand and a clay remains a clay, as far as practical considerations are concerned. Changes in texture may be made on a small scale by mixing two soils, but this is not practicable in the field.

63. Soil separates and mechanical analysis. — The soil particles, varying in size as they do, may be separated into arbitrary divisions, according to their diameters. The various groups are designated as soil separates, and the process of making the separation and determining the percentage of each group present is called mechanical analysis. There are a large number of classifications, or groupings, of the soil particles, as well as several methods of bringing about the actual separation. The grouping and method of mechanical analysis most generally used in this country is that devised by the United States Bureau of Soils.[1] Other methods[2] are more nearly accurate, but speed as well as precision is necessary in this work. A Swedish classification[3] of soil particles has been adopted by the Committee on Mechanical Soil Analysis,[4] appointed

[1] Briggs, L. J., and others. The Centrifugal Method of Soil Analysis. *U. S. D. A., Bur. Soils, Bul. 24.* 1904.

[2] For a detailed discussion of all methods of mechanical analysis, see Wiley, H. W. Agricultural Analysis, Vol. I, pp. 165–370. Easton, Pa. 1906.

[3] Atterberg, A. Die Mechanische Bodenanalyse und die Klassifikation der Mineralböden Schwedens. Internat. Mitt. f. Bodenkunde, Band II, Heft 4, Seite 312–342. 1912.

[4] Schucht, F. Über die Sitzung der Internationalen Kommission für die Mechanische und Physikalische Bodenuntersuchung in Berlin am 31. Oktober 1913. Internat. Mitt. f. Bodenkunde, Band IV, Heft 1, Seite 1–31. 1914.

by the Second International Agro-Geological Congress, which met in Stockholm in 1910. In simplicity and facility of interpretation the last-named grouping seems at least equal to that of the Bureau of Soils. Since a number of methods of mechanical analysis have been devised during the evolution and study of soil separation, it is necessary to be conversant with the principles involved and with at least two or three of the most successful modes of procedure.

64. Principles of mechanical analysis. — The various methods of mechanical analysis may be grouped according to the agents employed in the separation. The outline is as follows: —

Outline of systems of mechanical analysis

1. *Sieve* — Wet or Dry (Used to separate sands in practically all methods)
2. *Air* (Cushman's air elutriator)
3. *Water*
   - In motion
     - Gravity (Schöne's elutriator and Hilgard's churn elutriator)
     - Centrifugal (Yoder's centrifugal elutriator)
   - At rest
     - Gravity (Osborne's beaker method and Atterberg's modified silt cylinder)
     - Centrifugal (Bureau of Soils method)

In the consideration of such an outline, certain of the general methods proposed may be dismissed without further parley since they are inadequate for the separation

in question. Sieves of all kinds have the one great disadvantage that their meshes cannot be made small enough to separate the finer grades of soil. When one considers that many soil particles are less than .005 millimeter in diameter, the inadequacy of sieve separation becomes apparent. However, sieves may be used in connection with other methods as an easy way of dealing with the larger soil particles. Air in motion[1] is inadequate, as it can be used only for very fine particles. Even with these the separation is slow and inaccurate, because of the tendency of the dry particles to cohere. These two methods have therefore been largely abandoned as distinct methods, and water is used as the medium of separation in all the modern systems of mechanical analysis.

The principle involved in the subsidence of soil particles in water, whether the force of gravity or centrifugal force is utilized, is recognized by every one. When fragments of rock or soil are suspended in water, they tend to sink slowly, and it is a well-recognized fact that other things being equal, the rate of settling depends on the size of the particle. As the particle is decreased in size, its weight decreases faster than the surface exposed to the buoyant force of the water. As a consequence, the rapidity with which the soil particles settle is proportional to their size. The suspension of a sample of soil would therefore be the first step in mechanical separation by water; the second step would be subsidence and the withdrawal of each successive grade of particles as it slowly settled; the third step would be determination of the percentage of each grade, or group, of particles

[1]Cushman, A. S., and Hubbard, P. Air Elutriation of Fine Powders. Jour. Amer. Chem. Soc., Vol. 29, No. 4, pp. 589-597. 1907.

as based on the original sample. This is precisely what every method of mechanical analysis in which water is utilized aims to do, although often the apparatus and technique are excessively complicated.

66. Mechanical analysis by water in motion. Schöne's elutriator. — Any appliance that is designed to separate particles of different sizes by water in motion may be designated as an elutriator. *One of these, commonly used in* Europe, is called Schöne's elutriator.[1] This utilizes hydraulic force. In it, the upward current of water ascends a conical glass tube (see Fig. 11) from a narrow curved inlet tube below. The soil sample present in the inlet tube is kept agitated by the current. It is evident that by regulating the rate of flow of the water, different sizes of particles will be carried away over the top of this conical glass tube. Thus by a gentle flow only fine grades will be separated, while by increasing the current larger and still larger particles will be carried upward against the force of gravity.

FIG. 11. Schöne's elutriator for mechanical soil analysis with water in motion.

There are three objections to this method. First, the entrance tube may become clogged, and, unless a very small

[1] Schöne, E. Ueber Schlämmanalyse. Bul. Soc. imperiale des Naturalistes de Moscou, 40, Part I, p. 324. 1867. Über Schlämmanalyse und einen neuen Schlämmapparat. Berlin, 1867. Also see Wiley, H. W. Agricultural Analysis, Vol. I, pp. 231-241. Easton, Pa. 1906.

quantity of soil is used, the mass is not kept properly agitated; secondly, convex currents are set up in the conical glass tube, which vitiates the results; and, thirdly, the separate particles tend to coalesce into granules. It is evident that in any separation of soil particles all granulation must be avoided. This is usually accomplished by shaking or boiling the sample previous to the determination. The tendency toward granulation during the process of separation itself is fatal to accuracy, as compound particles carrying a large number of small grains would fail to pass over at water-current velocities corresponding to their component parts.

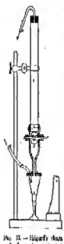

Fig. 12. — Hilgard's churn elutriator for mechanical soil analysis of particles above .01 mm. in diameter: (a), intake; (b), stirrer; (c), screen; (d), separating chamber; (e), outlet tube

66. **Hilgard's churn elutriator.** — The errors of the Schöne apparatus are obviated to some extent by Hilgard's,[1] the principle of operation remaining exactly the same. In Hilgard's elutriator the deflocculated soil sample is introduced into the base of a cylindrical tube (see Fig. 12) in which is placed a rapidly revolving stirrer. This is designed to counteract convex currents and to prevent the

[1] Hilgard, E. W. Methods of Physical and Chemical Soil Analysis. Ann. Rept. California Agr. Exp. Sta., pp. 241–257. 1891–1892.

formation of compound particles. A screen placed just above the stirrer serves to prevent the whirling motion from being communicated to the ascending column of water in which the separation occurs. The various grades in the separation are regulated by the rate of water flow. With this apparatus it is necessary to remove the finer particles below .01 mm. in diameter by subsidence previous to the determination.

While this method is very nearly accurate and will give a separation of the various grades such as is impossible with most other methods, it is impracticable in ordinary soil work. The large quantity of water which is used in carrying over each grade, and which of course must be evaporated before the sample can be weighed, is the first objection. The length of time necessary for the separation, and the cost of the apparatus, are two additional objections urged against it. As mechanical analysis is used largely in determining soil texture, rapidity and ease of operation are of more importance than the extremely accurate separation of the particles.

67. Yoder's centrifugal elutriator. — One of the objections to the methods already described is the length of time necessary for a determination. This is due to the fact that very fine particles subside in water very slowly. In order to hasten the separation, Yoder[1] devised a machine in which hydraulic force may be supplemented by a centrifugal pull. This ingenious apparatus consists of an elutriator bottle (see Fig. 13) mounted in a centrifuge. The muddy water is introduced into the bottle at the center of the centrifuge. It then passes to the bottom of the bottle and back again to the

[1] Yoder, P. A. A New Centrifugal Soil Elutriator. Utah Agr. Exp. Sta., Bul. 89. 1904.

outlet, carrying with it a sediment the size of which depends on the rate of water flow and the strength of the centrifugal force. The bottle is so designed that particles in all parts of the separating chamber are subjected to the same force, no matter what their distance

FIG. 13.—Separatory bottle of Yoder's centrifugal elutriator. (B), Bottle; (e), intake; (a), tube for conducting liquid to bottom of separatory bottle; (o), outlet; (C), centrifuge; (w), counterpoise.

from the center of the centrifuge may be. The apparatus can be used only for separating particles less than .03 millimeter in diameter. It is open to the same objections that apply to Hilgard's machine, besides being very much more complicated and delicately adjusted. It is too costly an apparatus for ordinary work.

68. Mechanical analysis by water at rest. Osborne's beaker method.—One of the earliest and most nearly accurate methods to be perfected was the separation of the various grades of soil by simple subsidence in a column of still water. This is commonly spoken of as the Osborne beaker method.[1] The determination is very simple. The soil sample is first fully deflocculated and thrown into suspension, each particle functioning separately. Beakers are commonly used as containers, but

[1] Osborne, T. B. Methods of Mechanical Soil Analysis. Ann. Rept. Connecticut Agr. Exp. Sta., 1886, pp. 141–158; 1887, pp. 144–162; 1888, pp. 154–157.

any vessel that is relatively deep will do for the determination. The larger particles, or sand grains, will of course settle first, and the finer silts and clays may be decanted off. As the sands carry finer particles down with them, the suspension and subsidence must be repeated a number of times. The finer particles, separated thus and decanted, may be further subdivided in the same manner. The time necessary for such decantation as will leave in suspension only particles below a given size is determined by the examination of a drop of the suspension under a microscope fitted with an eyepiece micrometer. In this way the size of the particles decanted may be accurately measured.

The three steps in this method of separation are: deflocculation of the sample; separation by successive subsidence and decantation; and evaporation to dryness of the separates and their calculation to a percentage based on the original sample. The method, however, is slow, as the time necessary for each subsidence of the finer particles is very great and the number of individual subsidences is large. Neither is the method capable of the refinement of separation which is possible with certain of the elutriators. As a consequence it has been superseded by methods that utilize centrifugal force for the finer separations while retaining gravity for removing the various grades of sand.

69. Atterberg's modified Appiani[1] silt cylinder (Fig. 14).—This method[2] is similar to the beaker method in

[1] Appiani, G. Ueber einen Schlämmapparat für die Analyse der Boden- und Thonarten. Forsch. a. d. Gebiete d. Agri-Physik, Band 17, Seite 291–297. 1894.

[2] Atterberg, A. Die Mechanische Bodenanalyse und die Klassifikation der Mineralböden Schwedens. Internat. Mitt. f. Bodenkunde, Band II, Heft 4, Seite 312–342. 1912.

general principle, but a special apparatus is employed by means of which the various grades obtained by sedimentation are siphoned off instead of decanted. The cylinder is really a modified Wahnschaffe cylinder,[1] such as was used in early soil analyses for drawing off the various suspensions except that the siphon is placed outside the cylinder instead of inside.

FIG. 14. – Atterberg's silt cylinder for the mechanical analysis of soil by sedimentation.

The cylinder (die Schlämmapparat) as used by Atterberg is about 25 centimeters high, with a glass pedestal and a ground glass stopper. It is graduated at 5, 10, 15, and 20 centimeters upward from the bottom. The same distance is divided also into 16 divisions at the left of the first graduation. The latter graduation is used in the separation of the clay (Schlamm), so that the height of the sedimenting column may be regulated according to the time available for the settling process. An outside siphon, 4 to 5 millimeters wide, is attached to the cylinder at the bottom for the drawing of the liquid when the sedimentation is complete. The top of this siphon is opposite the 5-centimeter mark on the cylinder. Cylinders of this size are used only for the separation of particles below .2 millimeter in diameter; for larger particles a somewhat taller cylinder is used, with a siphon of the

[1] Wiley, H. W. Agricultural Analysis, pp. 205–207. Easton, Pa. 1906.

same width as for the finer particles. The graduation of the cylinder and its diameter are the same as described above.

A 20-gram sample of soil is used with this apparatus, and deflocculation is brought about by means of a stiff brush. The sample is reduced to a paste in a porcelain dish, and then, by alternate working with the brush and decanting, all the particles are thrown into separate suspension. A deflocculating chemical is used in humus soils, in order to hasten the process and counteract the effect of the organic matter. As in the beaker method, the size of the various grades of separation may be varied according to the will of the operator.

70. *Centrifugal soil analysis.*—Of the centrifugal methods used in mechanical analysis, that employed by the United States Bureau of Soils[1] is the most successful. A 5-gram sample of well-pulverized soil is put into a shaker bottle of about 250 cubic centimeters capacity (see Fig. 15). This bottle is filled about two-thirds full of water, so that in shaking the disintegrating force of the liquid may be utilized. A few drops of ammonia are added, to dissolve the organic matter and to make deflocculation easier. The sample is then agitated in the bottle until disintegration is complete. This period ranges from five to twenty hours, depending on the sample.

The separation of the silt and the clay from the sands is made in the shaker bottle by simple subsidence, the time for decantation being determined by a microscopic examination of a drop of the suspension. The silt and

[1] Fletcher, C. C., and Bryan, H. Modification of the Method of Soil Analysis. U. S. D. A., Bur. Soils, Bul. 84. 1912.

the clay are decanted directly into a test tube fitted into a centrifuge (see Fig. 15). Whirling at the rate of 800 to 1000 revolutions a minute will cause the subsidence of the silt to the bottom of the test tube in a few minutes. The clay is thus decanted. The microscope is necessary here, in order to determine when the settling of the silt is complete. As small particles tend to cling to the larger particles, the entire operation must be repeated

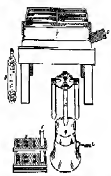

Fig. 15. — Apparatus for centrifugal mechanical analysis of soil, showing shaker bottle, shaker, centrifuge, and test tubes.

several times; therefore the processes of gravity subsidence and centrifugal subsidence are carried on side by side, material being constantly poured from the shaker bottle into the centrifuge tubes and from the test tubes into the receptacles for the clay.

The centrifuge is usually large enough to allow the separation of several duplicate samples at once. The various separates made by this method are dried and

weighed. The sands, which are obtained in bulk, are further separated by sieves into the grades desired. Where a large quantity of organic matter is present, it must be determined and included in the final report on the sample.

This method of mechanical analysis as perfected by the Bureau of Soils has been very generally adopted by soil workers. It has many advantages over other methods. In the first place, it is rapid, often requiring only hours where other methods take days for completion; secondly, it is simple, and the technique of the separation is easily acquired; thirdly, in the decantations no very large amount of water is accumulated with the separates, except for the clay, and thus the time and cost of evaporation is diminished. The clay, moreover, may be as accurately determined by difference as by direct methods, thus allowing a further saving of time. The cost of the equipment for this method is low. The apparatus itself is simple, and is carried by all standard chemical companies. The same cannot be said of the various elutriator mechanisms. While the method is accurate only within one per cent, it is sufficiently precise for practical purposes, especially in class determination, for which mechanical analysis is generally utilized.

71. **Classification of soil particles.** — With the large number of different methods of mechanical soil analyses there has arisen a large variation in textural groupings expressed in diameter of particles. This would naturally occur because of the differences in degree of refinement which the various methods of separation allow, and also because of the uses which the investigators wished to make of such analyses. Some of the best-known groupings are given below :

VARIOUS TEXTURAL CLASSIFICATIONS USED IN THE MECHANICAL ANALYSES OF SOILS. EXPRESSED IN DIAMETER OF PARTICLES IN MILLIMETERS

SEPARATE	OSBORNE[1]	HILGARD[2]	BUREAU OF SOILS[3]	ENGLISH[4]	ATTERBERG[5]
1	3.000	3.000	2.000	1.000	20.000
2	1.000	1.000	1.000	.200	2.000
3	.500	.500	.500	.040	.200
4	.250	.300	.250	.010	.020
5	.050	.160	.100	.002	.002
6	.010	.120	.050		
7		.072	.005		
8		.047			
9		.036			
10		.025			
11		.016			
12		.010			

Of these classifications only three need claim our attention — that of the Bureau of Soils, that of Hall and Russell (the English classification), and that devised by Atterberg. These represent the groupings used in expressing mechanical soil analyses in the United States,

[1] Osborne, T. B. Methods of Mechanical Soil Analysis. Ann. Rept. Connecticut Agr. Exp. Sta., 1886, pp. 141–158; 1887, pp. 144–158; 1888, pp. 154–157.

[2] Hilgard, E. W. Methods of Physical and Chemical Soil Analysis. Ann. Rept. California Agr. Exp. Sta., 1891–1892, pp. 241–257.

[3] Briggs, L. J., and others. The Centrifugal Method of Soil Analysis. U. S. D. A., Bur. Soils, Bul. 24. 1904.

[4] Hall, A. D., and Russell, E. J. Soil Surveys and Soil Analyses. Jour. Agr. Science, Vol. IV, part 2, pp. 182–223. 1911.

[5] Atterberg, A. Die Mechanische Bodenanalyse und die Klassifikation der Mineralböden Schwedens. Internat. Mitt. f. Bodenkunde, Band II, Heft 4, Seite 312–342. 1912.

in England, and in Continental Europe, respectively. As to which is the best for an interpretation and expression of textural qualities it is difficult to say. They are all arbitrary, yet they are all extremely useful. It therefore seems immaterial which one is employed. It would be better, of course, if the classification were uniform for all countries; correlation of soil properties would thereby be easier.

72. Bureau of Soils classification. — As the grouping established by the United States Bureau of Soils is met with in all of our soil literature, and as it is really the standard classification for this country, a closer consideration of it may be profitable. The discussion of the properties exhibited by the various separates, and of the interpretation and value of a mechanical analysis, will therefore be made with this classification as a basis. By way of illustrating the grouping and the mode of expressing a mechanical analysis the results obtained from two distinctly different soils are given below: —

MECHANICAL ANALYSES[1] OF A DUNKIRK FINE SANDY LOAM AND A DUNKIRK CLAY

SEPARATES	SIZE IN MILLIMETERS	FINE SANDY LOAM	CLAY
		%	%
Fine gravel	2-1	1	1
Coarse sand	1-.5	2	2
Medium sand	.5-.25	3	2
Fine sand	.25-.10	22	6
Very fine sand	.10-.05	35	7
Silt	.05-.005	27	39
Clay	below .005	10	43

[1] Soil Survey Field Book, pp. 153, 154. U. S. D. A., Bur. Soils. 1906.

73. Physical character of the separates. — It is immediately apparent that as these groups vary in size they must exhibit properties, especially physical ones, which are widely different. These properties should in turn be imparted to the soil of which the separates form a part. If we are conversant with these various values, a mechanical analysis should reveal to us at a glance certain soil conditions which may or may not be conducive to the best plant growth.

The clay particles are very minute; many of them are so small as to be invisible under the ultramicroscope. They are really shreds and fragments of minerals, and are jagged and angular in outline. They are highly plastic, and when rubbed together they become sticky and impervious. They shrink much on drying, with the absorption of considerable heat. On being wet again they swell with the evolution of the heat already taken up. Many of the particles exhibit the Brownian movement and will remain in suspension for an indefinite period. The finer part of the clay makes up a portion of that indefinite group of material in the soil called colloids, which because of their fineness of division (molecular complexes) exhibit certain well-defined properties, of which adsorption of moisture and salts in solution, and high plasticity and cohesion, are the most important from a soil standpoint. Silt exhibits the same qualities as clay, but to a much less marked extent. The presence of clay in a soil imparts to it a heavy texture, with a tendency to slow water and air movement. Such a soil is highly plastic, but becomes sticky when too wet and hard and cloddy when too dry. The expansion and the contraction on wetting and drying are very great. The water-holding capacity of a clay soil is high.

The sands and the gravel, because of their sizes, function as separate particles. They are irregular and rounded, the continued rubbing that they have received being sufficient to have effaced their angular character. They exhibit very low plasticity and cohesion, and as a consequence are little influenced by changes in water content. Their water-holding capacity is low, and because of the large size of the spaces between each separate particle the passage of water is rapid. They therefore facilitate drainage and encourage good air movement. In all the grades of sand the separate particles are visible to the naked eye, a condition impossible with the silt and clay groups. Soil containing much sand or gravel, therefore, is of an open character, possessing good drainage and aeration, and is usually in a loose friable condition.

74. Mineralogical characteristics of the separates. — From the mineralogical standpoint there are usually considerable differences in the soil separates. These differences would naturally be expected to occur particularly in residual soils, because of the differentiating tendencies of weathering. Quartz would naturally persist, and because of its slow solubility would very soon make up most of the larger soil grains. Other minerals, such as the feldspars, hornblende, augite, and the like, being less persistent as the law of mineral resistance has already taught us, would be worn to fine shreds and be found as the main constituents of the silts and the clays. The following data sustain this assumption regarding the mineralogical characteristics of some of the soil groups as designated by the Bureau of Soils as well as furnish some interesting comparisons of some important soil provinces:

General Mineralogical Composition of the Sands and Silts of Various Soil Provinces of the United States[1]

Soil	No. of Samples	Minerals other than Quartz in	
		Sands	Silts
Residual	12	15%	21%
Glacial and loessial	9	12%	15%
Marine	4	5%	8%
Arid	3	37%	42%

It is to be seen immediately that in every case the silt carries a larger quantity of the important soil-forming minerals and a smaller quantity of quartz than does the sand. This reveals at least one of the reasons for the greater fertility and lasting qualities of fine-textured soils as far as agricultural operations are concerned. It is important to note, however, that, although quartz is the predominating mineral in sands, all the common soil-forming minerals are usually necessary. This merely serves to again emphasize the fact that all soils contain all the common minerals found in soil-forming rocks.

It is also interesting to note the general differences exhibited by the various soil provinces. The residual, glacial, and coastal plain soils possess minerals other than quartz in the order named. In the marine soils, in particular, this difference has largely come about by the disintegration and leaching that these soils have undergone during their formation. The arid soils, due to the suppression of chemical weathering and the activity

[1] McCaughey, W. G., and Williams, H. F. The Microscopic Determination of Soil-Forming Minerals. U. S. D. A., Bur. of Soils, Bul. 91. 1913.

of the physical agents, exhibit smaller quantities of free quartz. The silica in such soils is held as complex silicates, which very largely carry the elements that are so important in plant development.

Although these data are based on but a few samples, they are so concordant with what would naturally be expected that these general conclusions cannot be avoided.

75. **The chemical constitution of soil particles.** — The mineralogical examination of soils has revealed a larger percentage of such minerals as feldspars, mica, hornblende, and the like, in the finer separates. A larger percentage of the important plant-food elements would therefore be expected in these groups. The following data,[1] compiled from work performed by the United States Bureau of Soils, substantiate this assumption. —

Chemical Composition of Various Soil Separates

Soils	Number of Samples	Percentage of P_2O_5			Percentage of K_2O			Percentage of CaO		
		Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Crystalline residual	6	.07	.22	.70	1.60	2.37	2.86	.50	.82	.94
Limestone residual	3	.28	.23	.37	1.46	1.83	2.62	12.30	10.90	9.98
Coastal plain	4	.03	.10	.34	.37	1.32	1.07	.07	.17	.56
Glacial and loessial	10	.15	.23	.86	1.72	2.30	3.02	1.28	1.30	2.69
Arid soils	3	.19	.24	.49	3.05	4.15	6.05	4.00	9.22	8.13

It is seen that on the average the soils with finer particles are richer in phosphoric acid, potash, and lime, than those of coarser texture, the only exception in this case being in the lime of the residual limestone soils. The arid soils present a less marked difference in the sands,

[1] Failyer, G. H., and others. The Mineral Composition of Soil Particles. U. S. D. A., Bur. Soils, Bul. 54. 1908.

silts, and clays than the representatives of the other soil provinces; this is true also of the glacial soils, but to a less degree. Under such conditions of weathering the sands have not as yet been depleted of their stores of essential elements. Average data compiled from a number of soil analyses by Hall,[1] presented below, tend to corroborate the data already noted and that obtained by Loughridge[2] of California:

COMPOSITION OF SOIL SEPARATES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	P_2O_5
Coarse sand (1–.2 mm.)	93.9	1.6	1.2	.4	.5	.8	.05
Fine sand (.2–.04 mm.)	94.0	2.0	1.2	.5	.1	1.5	.1
Silt (.04–.01 mm.)	89.4	5.1	1.5	.8	.3	2.3	.1
Fine silt (.01–.002 mm.)	74.2	13.2	5.1	1.6	.3	4.2	.2
Clay (Below .002 mm.)	53.2	21.5	13.2	1.6	1.0	4.9	.4

76. Value of a mechanical analysis. — It is now evident that the proper interpretation of a mechanical analysis throws considerable light on the probable physical and chemical properties of a soil. To the trained observer the preponderance of sand or clay signifies certain physical properties which may affect the plant not only mechanically, but physiologically as well, through varia-

[1] Hall, A. D., and Russell, E. J. Soil Surveys and Soil Analyses. Jour. Agr. Science, Vol. IV, Part 2, p. 190. 1911. Also a Report of the Agriculture and Soils of Kent, Surrey, and Sussex. Board of Agriculture and Fisheries. 1911.

[2] Loughridge, R. H. On the Distribution of Soil Ingredients among Sediments Obtained in Silt Analyses. Amer. Jour. Sci., Vol. VII, p. 17. 1874.

In this connection see also Pushner, Dr. Über die Verteilung von Nährstoffen in den Verschiedenen Feinen Bestandteilen des Bodens. Landw. Ver. Stat., Band 60, Seite 468–470. 1907.

tions in air and water movements. The chemical phases of such an interpretation are also worthy of consideration, as the proportion of the various separates determines whether the essential plant-food elements will be present in sufficient quantities to permit normal crop growth. Thus in a general way the mechanical analysis of a soil not only enlightens us as to the general properties of a given soil, but is to some extent a criterion of agricultural value and crop adaptation. Some authors[1] maintain that in the investigation of any soil a mechanical analysis should first be made, as such an analysis throws so much light on the general qualities of a soil.

77. Soil class. — *Class* is a term used in relation to the texture, or size of particles, of a soil. Class differs from texture, however, in that it has reference rather to the particular properties exhibited by a soil than to any absolute grain size. As soils are not made up of particles of the same size, a blanket term is needed which will not only give an idea of the texture of the soil, but also name it in such a manner as to reveal general peculiarities and properties. We may have any number of classes, depending on the sizes of the soil grains carried.

These class names have originated through long centuries of agricultural operations, but of late they have been more or less standardized because of the necessity of a definite nomenclature. In general the names used for the soil classes are the same as are used in mechanical analyses to designate the soil separates. This is rather unfortunate, but it obviates the increase of technical terms and a little care will prevent confusion in this regard.

Another word introduced by common usage is *loam*.

[1] Hall, A. D., and Russell, E. J. Soil Surveys and Soil Analyses. Jour. Agr. Science, Vol. IV, Part 2, p. 199. 1911.

Loam, from the technical standpoint, refers to a soil possessing in about equal amounts the properties imparted by the various separates. If, however, we have practically the same condition but with one size of particle predominating, the name of that particular separate is prefixed, giving still more data regarding the soil in question. Thus a loam in which clay is dominant will be classified as a clay loam. In the same way we may have a sandy loam, a sandy clay loam, a gravelly sandy clayey loam, and so on. The number of soil classes that may occur is therefore rather large, ranging from coarse gravel, through the various grades of sands, to silts and clays.

A few of the common classes, with their mechanical analyses, are listed below:—

Mechanical Composition of Various Soil Classes[1]

	Number of Samples	Fine Gravel	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay
Coarse sands . .	135	12	31	19	20	6	7	5
Sands	401	2	15	33	37	11	7	5
Fine sands . . .	511	1	4	10	57	17	7	4
Sandy loams . . .	1141	4	13	12	25	13	21	12
Fine sandy loams .	634	1	3	4	32	24	24	12
Loams	670	2	5	5	15	17	40	16
Silt loams	1368	1	2	1	4	11	65	15
Sandy clays . . .	162	3	8	8	30	12	13	27
Clay loams . . .	718	1	4	4	14	13	38	30
Silty clay loams . .	765	0	2	1	4	7	61	25
Clays	1020	1	3	2	8	8	36	42

[1] Whitney, M. The Use of Soils East of the Great Plains Region. U. S. D. A., Bur. Soils, Bul. 78, p. 13. 1911.

It is evident that a mechanical analysis of a soil is nothing more or less than an expression of class, and the inferences that may be derived from either are the same. This leads to a consideration of class determination.

98. **Determination of class.** — The common method of class determination is that employed in the field. It consists in examination of the soil as to color, an estimation of its humus content, and, especially, a testing of the "feel" of the soil. Probably as much can be judged as to the texture and class of a soil by merely rubbing it between the thumb and the fingers as by any other superficial method. This is a method used in all field operations, especially in soil survey work. The accuracy of the determination depends largely on experience. Inaccuracies are likely to occur in distinguishing between the various finer grades of soil; for this reason more nearly exact methods are necessary at times, especially in checking *soil survey work or in carrying out investigations* in which absolute accuracy is required.

As a mechanical analysis of a soil is really a percentage expression of texture, it presents an exact method for class determination. For detailed work somewhat complicated tables[1] have been arranged, but the following diagram (Fig. 16), devised by Whitney,[2] presents a simple method for the identification of a soil from a mechanical analysis. The convenience of this triangular representation may be tested by the use of the average analyses, already presented on a previous page.

[1] Bur. of Soils, Soil Survey Field Book, p. 17. U. S. D. A., Bur. Soils. 1906. Also, Bur. Soils, Bul. 78, p. 12. 1911.

[2] Whitney, M. The Use of Soils East of the Great Plains Region. U. S. D. A., Bur. Soils, Bul. 78, p. 18. 1911.

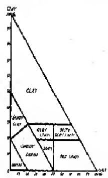

FIG. 16. — Diagram for the determination of soil class from a mechanical analysis.

73. **The significance of texture and class.** — Soil texture and class are the basis for all soil consideration, whether regarding some specific property or a general condition such as crop adaptation. No matter what the phase of soil study may be, texture and class are sure to have some important influence and must be included in the investigation. From observations in practice, certain crops have been found to be adapted to certain kinds of soil — as clay loam for wheat, silt loam for corn, loam or sandy loam for potatoes, clay or clay loam for timothy, and so on. Two authors[1] have determined the mechanical qualities of soils well adapted to certain crops. An average of their analyses is given below: —

[1] Hall, A. D., and Russell, E. J. Soil Surveys and Soil Analyses. Jour. Agr. Science, Vol. IV, Part 2, p. 207. 1911.

THE MECHANICAL ANALYSIS OF SPECIFIC CROP SOILS

	Wheat ([illegible] samples)	Barley ([illegible] samples)	Potato ([illegible] samples)	Hop ([illegible] samples)	Fruit ([illegible] samples)
Fine gravel .	1.4	1.2	.9	1.2	1.0
Coarse sand .	3.7	16.3	20.1	4.8	6.8
Fine sand . .	24.5	32.0	43.5	33.8	42.0
Silt	33.0	18.2	21.0	38.8	28.3
Fine silt . .	12.8	8.9	6.4	8.7	7.3
Clay . . .	20.0	11.9	9.7	12.1	10.9

The soil particle can thus be seen to function in no insignificant manner regarding plant condition. Its size, its physical relationships, its chemical composition, and the conditions imposed by a preponderance or a limitation in its various grades, are of vital importance. Soil texture and soil class, therefore, are terms of constant usage in soil discussion and study, whether the viewpoint is practical or purely theoretical.

CHAPTER VII

SOME PHYSICAL PROPERTIES OF THE SOIL

WHILE texture is of great importance in the determination of the physical and chemical nature of a soil, it is evident that the arrangement of the particles also exerts considerable influence. The term texture refers to the size of the soil particles; the term structure is used in reference to their arrangement, or grouping. It is at once apparent that certain conditions — such, for example, as air and water movement, heat transference, and the like — will be as much affected by structure as by texture. As a matter of fact, the great changes wrought by the farmer in making his soil better suited as a foothold for plants are structural changes rather than changes in texture. The compacting of a light soil or the loosening of a heavy soil is merely a change in arrangement of the soil grains. It is of interest, therefore, to ascertain the probable arrangement of the particles in any soil.

80. Arrangement of soil particles (Fig. 17). In any consideration it is the easier way to advance from the simple to the complex. Therefore in the explanation of structural relationships a theoretical condition will be dealt with first, after which the discussion will proceed to the intricate condition existing in the soil. Assuming that this theoretical condition consists in spherical particles all of the same size, we find these particles susceptible

to two different arrangements: (1) in columnar order, with each particle touched in four points by its neighbors; and (2) the oblique, in which each particle is in contact with six of its neighbors. The possible pore space in the first case is 47.64 per cent, while that in the second case is 25.95 per cent. The amount of this pore space is uninfluenced by the size of the particles, provided they are round and all of the same volume.

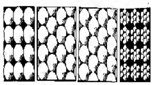

FIG. 17. — Ideal arrangements of spherical particles, showing, from left to right, columnar, oblique, compact, and granular orders.

To any one of practical experience it is a well-known fact that the soil particles are not homogeneous as to size, and neither do all the particles function as simple grains, being gathered together in groups called granules, or crumbs. A small particle of soil may be made up of a number of very small grains. This will modify the ideal condition as described above, giving two additional conditions — first, a mixture of spherical grains of different sizes, and, secondly, a condition in which the large grains are complexes made up of numerous small particles. A mixture such as is presented by the first of these conditions, in which the small grains fit in between the larger ones, will result in a reduction of pore space. The pore space will fall below 25.95 per cent and approach zero. A real soil having such restricted pore space is

designated as being in a puddled condition. This condition is detrimental to plant growth, for it not only impedes root development and extension, but also prevents the circulation of air and water, a function necessary for proper soil sanitation. In the second condition an increase in pore space must occur, as each large grain presents considerable internal air space. If the granules as well as their component particles were arranged in columnar order, the pore space would reach the high percentage of 72.58. Under natural conditions, then, the pore space might range from zero plus to about 73 per cent.

However, not only are the particles of a normal soil not of the same size, but they are far from round. A soil, as already demonstrated, ordinarily presents varying amounts of particles, ranging in size from stone and coarse gravel to the very finest clay. These particles may also differ in shape, varying from almost perfect spheres to flakes, chips, and fragments of every conceivable form. Therefore the laws that apply to the ideal condition will hold only in a general way in a normal soil. It is evident, first, that the more compact the soil, the less is the pore space; secondly, that it is possible to so manipulate a soil as to work the small particles in between the larger ones and create an impervious or puddled condition; and, thirdly, that by the forming of granules the pore space of a soil may be increased to a high percentage.

From the standpoint of size and arrangement of particles there are really two classes of soils, those of single grain structure and those that are granular. In the former each particle functions separately. In order to do this the particles must be large. This condition is found in

sand. In such soil would naturally be found also a medium to low pore space, just as has been exemplified in the ideal condition described above. In granular soils, the granules, being made up of small particles, present much internal pore space. This condition occurs only in fine soils, such as loams, silts, and clays, since large particles will not cohere firmly enough to produce a crumb structure. A fine-textured soil, which will puddle more readily than a coarser one, is thus saved from a semi-impervious condition by this tendency toward granulation.

The ideal soil condition might be considered to be most likely to occur in a loam (Fig. 18). In loamy soil some of the particles are large and function separately; others are medium in size and tend to form the nuclei around which smaller particles may cluster to form granules, or crumbs. There are thus a few large pore spaces which facilitate drainage, and numberless small openings in which water is retained. Air therefore finds easy movement, and sanitation is promoted. In such a condition the organic matter plays an important part. This exists usually as dark, partially decayed material. It pushes apart the grains and lightens the soil, and contributes much in bringing about the loamy condition so favorable to plant development. Because of its water-holding capacity also it proves a valuable addition. Thus with

FIG. 18. The arrangement of particles in loamy soil of good structural condition. (a), large granule; (b), small sand particle; (c), large pore space; (d), small granule with small interstitial spaces; (e), large sand grain.

particles of varying sizes, of a structure partly single-grain and partly granular, to which has been added by natural means sufficient organic matter in an advanced stage of decomposition, we have the ideal soil conditions for plant development. Yet the same laws govern here in a general way as were found to function with homogeneous grains of spherical shape.

81. **The absolute specific gravity of the soil.** — The structural condition of any soil, be it single-grain, granular, or a favorable combination of the two, has considerable influence on certain other physical conditions. One of those most affected is the weight. The weight of a soil is determined by two factors: the weight of the individual particles, or the absolute specific gravity; and the amount of actual space taken up by such particles in any given volume. The latter is really a structural condition and is independent to some extent of the size of particles. The absolute specific gravity, or weight compared with an equal volume of water, of some of the common minerals is as follows:

Quartz	2.7	Apatite . . .	3.2
Orthoclase . . .	2.6	Gypsum . . .	2.3
Plagioclase . . .	2.7	Hematite . .	5.2
Mica	3.0	Limonite . . .	4.0
Olivine	3.4	Serpentine . .	2.6
Calcite	2.7	Chlorite . . .	2.2
Dolomite . . .	2.9	Talc	2.7

Although a great range is observed in the absolute specific gravities of these common soil-forming minerals, it must be remembered that such minerals as quartz and feldspar usually make up the bulk of a soil. As a consequence it has been found that the absolute specific

gravity of a purely mineral soil varies only between narrow limits, these being from 2.6 to 2.8. Nor has fineness any appreciable effect, as shown below by Whitney's[1] determinations on the various separates. —

SPECIFIC GRAVITY

Fine gravel (2–1 mm.)	2.647
Coarse sand (1–.5 mm.)	2.655
Medium sand (.5–.25 mm.)	2.648
Fine sand (.25–.10 mm.)	2.659
Very fine sand (.10–.05 mm.)	2.680
Silt (.05–.005 mm.)	2.698
Clay (below .005 mm.)	2.837

The only marked variation here observed is in the clay separate, and this may be due to the concentration of the iron-bearing silicates in this grade. However, for all practical purposes the average absolute specific gravity of a mineral soil may be placed at about 2.70. One condition that may vary this is the quantity of organic matter present. As the specific gravity of the soil humus usually ranges from 1.2 to 1.7, the more humus there is present, the lower will be the absolute figure for a given soil. A purely organic soil, such as muck or peat, presents a variable absolute specific gravity ranging from 1.5 to 2.0, according to the amount of wash it has received from external sources. Some humus-loam soils may drop as low as 2.1. Nevertheless for general calculations the average arable soil may be considered to have an absolute specific gravity of about 2.70.

52. Apparent specific gravity. — Since all soils contain more or less pore space, depending on textural and struc-

[1] Whitney, M. Some Physical Properties of Soils. U. S. D. A., Weather Bur., Bul. 4, p. 31. 1892.

tural conditions, the actual weight of the absolutely dry soil in any volume is of great importance. This is expressed as is the absolute specific gravity of any material, the weight of an equal volume of water being used as a unit. Because of their tendency to granulate, fine soils have a very large amount of pore space, as has been shown in the discussion of structure; it is to be expected, therefore, that they will weigh less in any particular volume than will soils made up of large particles. Coarse soils are heavy soils, as far as weight is concerned. Mineral soils may range in apparent specific gravity[1] from 1.10 to 1.30 for clay to 1.65 to 1.75 for sand. Humous loams may drop as low as 1.00, and muck often reaches the low figure of .80. The apparent specific gravity is always expressed on the basis of absolutely dry soil.

Fig. 19.—Cylinder for determining the apparent specific gravity of soil in the field. The cutting edge at (b) is drawn in somewhat to prevent excessive friction between the sides of the cylinder and the entering soil core.

In the field the apparent specific gravity of a soil may be determined by driving a cylinder of known volume into the ground and obtaining thereby a core of natural soil (see Fig. 19). By weighing the soil and then determining the amount of water that it holds, the amount of absolutely dry soil may be ascertained. Dividing this by the weight of an equal volume of water gives the apparent specific

[1] See Whitney, M., Some Physical Properties of Soils. U. S. D. A., Weather Bur., Bul. 4. 1892.

gravity for that soil. A laboratory determination may be made by putting the soil into a receptacle of known volume and weighing it. From the weight of the absolutely dry soil and the weight of an equal volume of water, the apparent specific gravity may be calculated. This method will give only approximate results, however, as the structural relationships are more or less artificial. The only reliable method is the one first described.

83. **Actual weight of a soil.** — With the apparent specific gravity of a soil known, its weight in pounds to the cubic foot may be found by multiplying by 62.42. Soils may vary in weight from 68 to 80 pounds for clays and silts to 100 to 110 pounds for sand. The greater the humus content, the less is this weight to the cubic foot. A muck soil often weighs as little as 25 or 30 pounds. This weight, of course, is for absolutely dry soil and does not include the water present, which may be much or little, according to circumstances. The actual weight of a soil is often expressed in acre-feet. An acre-foot of soil refers to a volume of soil one acre in extent and one foot deep. In the same way we may have an acre-eight-inches or an acre-six-inches. The weight of an acre-foot of soil usually varies from 3,500,000 to 4,000,000 pounds; granulation and organic matter may modify this considerably. The value of knowing the actual weight of a soil lies in the possibility of calculating thereby the amount of water, the amount of humus, or the actual number of pounds of the mineral constituents present in the soil. Such information affords a ready means of comparing two soils as to their crop-producing capabilities.

84. **Pore space in soil.** — The pore space in soil is due largely to structural conditions. As already emphasized, the coarser the soil, the smaller is the aggregate

amount of internal space. Each individual space is larger under such conditions, and this accounts for the ready movement of water and air through such soils. A clay soil, while containing a very large amount of pore space, has the disadvantage of very minute individual pores. The large amount of space occurs because of the lightness of the particles and the tendency toward granulation. The small size of the individual spaces is a direct function of size of particle, or texture.

A very simple formula may be used for a determination of the percentage of pore space in any soil, provided the absolute and the apparent specific gravities are known: —

$$\text{Percentage of pore space} = 100 - \left[\frac{\text{Ap. Sp. Gr.}}{\text{Ab. Sp. Gr.}} \times \frac{100}{1}\right]$$

Thus a soil having an apparent specific gravity of 1.60 and an absolute specific gravity of 2.60 has 38.5 per cent of pore space; while in a soil in which the above figures are 1.10 and 2.50, respectively, the percentage of pore space is 56. The following figures, taken from King,[1] illustrate the relation that texture holds to total pore space in soils: —

	Percentage of Pore Space
Sandy soil	32.49
Loam	34.49
Heavy loam	44.15
Loamy clay soil	45.32
Clayey loam	47.10
Clay	48.00
Very fine clay	52.94

[1] King, F. H. Physics of Agriculture, p. 124. Published by the author, Madison, Wisconsin. 1910.

The pore space in any of these soils is, of course, subject to considerable fluctuation, especially in the surface soil, due to tillage and the incorporation of organic matter; hence a sandy loam might under certain conditions present more pore space than a silt or a clay loam. When soils are in the physical condition for the best plant growth, however, the rule holds that, the finer the soil, the greater is the pore space. The differences in pore space between the surface soil and the subsoil in Wisconsin are shown by King[1] as follows: —

	Weight per Cubic Foot	Percentage in Pore Space
First foot	79.0	52.2
Second foot	92.6	44.0
Third foot	104.6	36.8
Fourth foot	106.2	35.8
Fifth foot	112.0	32.9
Sixth foot	111.1	32.8

The pore space in a normal soil is occupied by water and air. If the water content is low, the air space is large, and vice versa. Thus the relationships of the total pore space and the size of the individual spaces to the amount of air and water contained, to their movement through the soil, to soil sanitation, to root extension, to bacterial action, and to cropping conditions in general, become apparent. It is the regulation of this pore space that is really studied in any structural consideration. The effect on plant growth of a change in pore space is the final test of its advisability.

[1] King, F. H. Physics of Agriculture, p. 111. Published by the author, Madison, Wisconsin. 1910.

85. The number of soil particles. — The number of particles in any given volume of soil is really determined by texture, and, as this number determines very largely the probable arrangement of the soil grains, structure becomes in turn dependent on the size of grain. Since soil particles run to very small diameters, the number in any given volume is very large, especially when we are dealing with fine-textured soils or with soils of compact structural condition. Any calculation of the number of particles present in a soil is open to considerable inaccuracy, first, because it is impossible to get a correct figure for the average diameter of the particles of any soil or of the various groups of separates that go to make it up, and, secondly, because it must be assumed in the calculation that the particles are spherical. This assumption is of course incorrect, as has already been demonstrated; but it must be entertained in order to obtain approximate ideas as to the number of grains in any soil.

The number of particles in any soil sample may be arrived at from a mechanical analysis and the diameters that limit each group. Using the average diameter of each group together with the percentage of the groups in a given sample, the number of particles may be calculated by the following formula: —

$$\text{Number of particles in a sample of soil} = \frac{\text{Weight of sample in grams}}{1/6\, \pi D^3 \times 2.70}$$

The formula $1/6\, \pi D^3$ is that used for determining the volume of a sphere, the diameter in this case being expressed in centimeters. The volume of the sphere, thus, is obtained in cubic centimeters, which must be multiplied by the absolute specific gravity of soil minerals, or 2.70,

in order that the weight in grams of a single soil grain may be obtained. A calculation by this method of the number of particles in a sandy loam is given below:—

Separates	Limits	Number of Particles to the Gram of Each Separate	Percentage in Sandy Loam	Approximate Number of Particles per Gram of Sandy Loam
Fine gravel	2–1 mm.	302	1	3
Coarse sand	1–.5 mm.	1,670	4	67
Medium sand	.5–.25 mm.	13,410	25	3,352
Fine sand	.25–.10 mm.	131,900	35	46,165
Very fine sand	.10–.05 mm.	1,676,500	20	335,300
Silt	.05–.005 mm.	35,884,000	10	3,588,400
Clay	below .005 mm.	45,660,000,000	5	2,283,000,000
				2,286,578,285

A very great error is introduced by this method, especially in assuming that the average size of particles for the clay separate is .0025 millimeter. As the clay particles may become molecular complexes and consequently are very, very small, it stands to reason that such an assumption is far from correct. Nevertheless, it gives a very good idea as to the immense number of grains that we have to deal with, even in the coarsest of soils. A few figures as to the approximate number of particles in various average soil classes of the United States,[1] as reported by the Bureau of Soils, are given below:—

[1] For mechanical analysis of these classes, see Chapter VI, p. 104.

APPROXIMATE NUMBER OF PARTICLES TO THE GRAM IN VARIOUS CLASSES OF SOIL IN THE UNITED STATES

CLASS	APPROXIMATE NUMBER OF PARTICLES
Coarse sands	2,293,146,300
Sands	2,287,251,842
Fine sands	1,620,176,893
Sandy loams	5,483,707,020
Fine sandy loams	5,485,060,147
Loams	7,232,679,042
Silt loams	6,868,546,064
Sandy clays	12,726,014,032
Clay loams	11,577,825,092
Silty clay loams	11,430,037,544
Clays	19,177,571,994

86. **Surface exposed by soil particles.** — Besides giving an actual numerical figure and an insight into the probable structural relationships of a soil, the approximate number of particles may serve still another purpose — that of enabling us to calculate the aggregate internal surface exposed by the soil grains. The surfaces of the grains hold more or less water according to their area, and they increase the amount of chemical and biological activities — functions so necessary to a continuous replacement in the soil solution of the elements withdrawn by the plant. The minerals in the soil are all very resistant to solution; if they were not, they would long ago have been leached away. Such materials, while almost insoluble, allow the amount of material going into solution to be notably increased by fineness of texture, although their solubility remains the same. The fineness of the particles, then, presents another significant feature besides those already pointed out.

Another important property of the surface of the grains is the tendency toward the retention of soluble material in a partially or wholly available condition for plant use. This power, designated as adsorption, is one exhibited to a high degree by fine soils, in which the individual pore spaces are small and the amount of surface exposed is large. It is an important factor to be observed in the addition to the soil of soluble fertilizing constituents. Adsorption may also, by bringing materials into closer contact, hasten or retard certain chemical actions. Reactions may thus be expected to go on in the soil that would not take place in the laboratory beaker. The relation of this adsorption to bacterial activity also cannot be overlooked.

The aggregate area presented by soil particles is very large, even for the coarser soils. With the finer soils, because of the immense number of particles, a figure is reached that is almost beyond comprehension. When the approximate number of particles and their sizes in any given weight of soil are known, the internal surface may be calculated by the following formula: —

$$\text{Surface} = \pi D^2 \times \text{number of particles}$$

As the estimation of the number of particles in a soil is so inaccurate, it is evident that a calculation of the surface exposed based on such a figure must be more in error.

However, to give some idea of the internal surface exposed by ordinary soils, the calculations made on a few of the average soil classes of the United States, already presented,[1] are given in the table on the following page.

[1] See Chapter VI, p. 104.

Approximate Internal Area exposed by Average Classes of United States Soils

	Square Inches per Gram	Square Feet per Pound	Acres per Acre-foot of 3,500,000 Pounds
Coarse sands	91	288	23,155
Sands	89	280	22,840
Fine sands . . .	79	348	20,014
Sandy loams	213	671	53,965
Fine sandy loams . .	222	690	56,180
Loams	294	925	74,410
Silt loams	307	967	77,700
Sandy clays	417	1313	105,540
Clay loams	430	1354	108,830
Silty clay loams . .	458	1442	115,910
Clays	653	2057	165,270

It is at once apparent that the amount of surface exposed by the soil grains of even a sand is tremendous. It is not to be wondered at that the slowly soluble minerals are able to supply sufficient food to the crop growing on the soil, when such a large amount of surface is continually available for chemical action. The figures presented for an acre-foot of soil are almost too large for adequate comprehension. It is quite evident that the finer the soil, the greater is the amount of internal surface. For example, a sandy loam weighing 90 pounds to the cubic foot would present 60,390 square feet of surface, while a clay weighing 75 pounds to the cubic foot would expose about 154,275 square feet. This is equivalent to 1.39 and 3.54 acres, respectively.

87. The effective mean diameter of soil particles. — It is very evident that the calculations presented above, both as to the number of particles and as to the internal

surface exposed, are far from correct, as we can arrive at no definite figures as to the average size of grain. Neither do we know the actual structural conditions. In considering these inaccuracies King[1] decided that we were in need of a single term which not only would give an indication regarding the size of grain, but also would carry with it definite ideas as to the arrangement of the particles, particularly as to the rate at which they would allow air and water to pass through. This would bring the considerations nearer to the plant, as permeability very largely determines the conditions for plant development. King, while he could obtain neither the mean diameter of particle nor the actual internal surface, found that he could determine with considerable accuracy, particularly in sands, the diameter of grain which if substituted for the actual one would permit under like conditions the same rate of air and water movement. This size of grain he designated as the effective mean diameter of particle for that particular soil.

The theory of the method is presented by Schlichter,[2] and is based on the flow of fluids through capillary tubes. From the observed rate of the flow of air through a soil column under controlled conditions, it is possible to calculate the effective diameter of the interstitial spaces. From these data the size of the spherical grains which would be necessary to form such pore spaces, or capillary tubes, is computed by appropriate formulae. Such a figure represents the effective mean diameter of the soil,

[1] King, F. H. Physics of Agriculture, pp. 119-120. Published by the author, Madison, Wisconsin. 1910.

[2] Schlichter, C. S. Theoretical Investigation of the Movement of Ground Waters. U. S. Geol. Survey, 19th Ann. Rept., Part II, pp. 301-384. 1899.

from which the effective surface exposed can be determined. Thus, designating a soil as having an effective mean diameter of particle of .0063 millimeter merely indicates that this particular soil shows an air and water movement the same as would be shown by a homogeneous soil with spherical particles of that diameter.

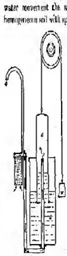

Fig. 30. – King's aspirator for the determination of the rate of air movement through soils. (G), Pressure gauge; (B), soil column; (L), water; (A), aspirator; (W), weight.

The apparatus[1] for the determination consists of a cylinder in which is placed a sample of air-dry soil, the pore space being carefully determined by weighing. The rate of air movement is then determined by connecting with an aspirator, the temperature and the pressure being constantly under control. The reading is usually calculated to a temperature of 20° C. The fact that the structural condition of the soil is likely to be disturbed in placing the sample in the aspirator tube detracts from the accuracy, especially in fine soils. Nevertheless King found his results fairly accurate, and showed that the calculated and the observed flow of water through

[1] King, F. H. Principles and Conditions of the Movements of Ground Water. U. S. Geol. Survey, 19th Ann. Rept., Part II, pp. 222–224. 1899. A complete discussion is given of King's ideas in this article, pp. 67–294.

sands[1] agreed rather closely (see Fig. 20). The effective diameter of the particles of some of our common soils, together with the effective surface exposed, is given below.[2]—

Soil.	Effective Diameter	Percentage of Pore Space	Effective Surface Exposed in One Cubic Foot of Soil.
Coarse sandy soil . .	.1432 mm.	34.0	8,318 sq. ft.
Sandy soil	.0755 mm.	34.4	15,870 sq. ft.
Sandy loam	.0303 mm.	38.8	35,880 sq. ft.
Loam	.0219 mm.	44.1	40,500 sq. ft.
Loamy clay soil . . .	.0140 mm.	45.3	71,300 sq. ft.
Fine clay soil	.0086 mm.	48.0	110,500 sq. ft.
Very fine clay . . .	.0049 mm.	52.9	173,700 sq. ft.

The method of King has certain advantages, besides giving an idea as to the number of particles, their internal surface, and the relation of this internal surface to soil conditions. In the first place, a single figure is used to express the size of particle; secondly, from this effective size of particle the probable rate of air and water movement may be calculated; and, thirdly, the number of particles and the internal surface calculated therefrom have a fairly definite relationship to the plant, as such figures are so closely correlated to the circulation of air and water.

[1] King, F. H. Physics of Agriculture, p. 123. Published by the author, Madison, Wisconsin. 1910.

[2] *Ibid.*, p. 124.

CHAPTER VIII

THE ORGANIC MATTER OF THE SOIL

ONE of the essential differences between a soil and a mass of rock fragments lies in the organic content of the former. Organic matter is a necessary constituent in order that finely ground mineral material may be designated as a soil and that it may grow crops successfully. Physical condition depends largely on the presence, and chemical reaction is greatly accelerated by the decay, of organic matter. In the process of soil formation its addition is more or less a secondary step. In residual débris the amount of organic matter held by the growing soil increases as the process of weathering goes on; in glacial soils, however, the matrix, or skeleton of the soil, is already formed before there is an opportunity for humus to become incorporated therein. The final result from the mixing of the minerals carrying numerous weathered and altered products with the decayed or partially decayed organic matter that is sure to accumulate, must be a mass much more complicated than either of the original constituents. It is hardly necessary to further emphasize the complexity of the average soil, the reasons therefor, and the difficulties in studying the question.

88. The source and distribution of organic matter. — The source of practically all soil organic matter is plant tissue. Some of this matter accumulates from the above-ground parts of plants that have died and fallen down

to become mixed with the surface soil; the remainder is a result of root extension and subsequent decay. The organic matter of the surface soil is derived from the tops and the roots of plants growing on it, while that of the subsoil is very largely a result of root extension and subsequent decomposition. The relationship between the humus content of three soils and the roots developed is shown by the following data presented by Kostytscheff[1] and quoted by Hilgard[2] and Wollny[3]:—

ROOT CONTENT AND PERCENTAGE OF HUMUS IN THREE RUSSIAN SOILS

	1		2		3	
DEPTH (inches)	ROOTS	HUMUS	ROOTS	HUMUS	ROOTS	HUMUS
6	100	5.4	100	8.1	100	9.6
12	81	4.8	69	5.2	80	7.2
18	67	3.6	48	3.9	70	6.7
24	47	2.5	35	2.8	58	5.6
30	47	2.5	20	2.1	38	3.6
36	35	1.8	18	1.5	32	3.1
42	26	1.2	0	.5	16	1.5
48	14	.8				
54	7	.3				

69. **Composition of plants.** — It is usual, in classifying the materials composing plant tissue, to group them under three heads — carbohydrates, fats and oils, and proteins.

[1] Kostytscheff, P. Les Terres Noires de Russie. Annales de la Sci. Agron., Tome II, pp. 165–191. 1887.
[2] Hilgard, E. W. Soils, p. 136. New York. 1906.
[3] Wollny, E. Die Zersetzung der Organischen Stoffe, p. 184. Heidelberg. 1897.

The carbohydrates, having the general formula of $C_x(H_2O)_y$, include such compounds as glucose, starch, cellulose, dextrose, cane sugar, and the like. The fats and oils may be represented in plants by such glycerides as butyrin, stearin, olein, palmitin, and the like. The proteins are by far the most complicated of the three principal compounds, as they may carry not only carbon, hydrogen, oxygen, and nitrogen, but also mineral elements such as sulfur, phosphorus, lime, iron, and other elements. They are compounds of high molecular weight and are mostly of unknown constitution. Simple proteins, such as albumin, globulin, protamins, and others, are found in plants, besides certain derived proteins such as proteoses and peptones. In addition to all these, there is a host of other compounds that have no small influence on the composition of the soil organic matter. Among these are the alkaloids, waxes, tannins, phenols and their derivatives, hydrocarbons, resins, acids, aldehydes, and others.

The original plant tissue, therefore, while fairly well known, as to chemical constitution, is far from simple. The degradation of such material, especially in the presence of complex mineral products, will evidently give rise at first to compounds no simpler; in fact, the chances are that the resulting compounds will be much more complicated. It is only later in the processes of decay that simple products result.

90. Decay of organic matter in soils. From the fact that weathering in general is a process of simplification, and since it is evident that the plant tissue as it enters the soil is so very complex, the general change that the organic matter undergoes must be one of simplification. This simplification, however, is very slow, and many of

the products built up are more complex than the original tissue. Most of this decay and simplification is due to that great group of organisms so universally present in soil, called bacteria. Some of these are putrefactive in their action, while others deal to a large extent with the products of the decomposition. All, however, exert a general simplifying influence. The action of such organisms may be direct, but is more likely to be enzymotic in its nature, and may take place either within or outside of the cell. A cycle is therefore set up, in which the higher plants and animals are occupied in building up, while bacteria are tearing down and reducing the residue of plant action to simple forms, such as can be ultimately utilized again in plant nutrition. The great importance of bacteria is thus evident, and the encouragement of their growth and function is clearly a part of good soil management.

When the complex molecules that make up plant tissue break down, they split along definite lines of cleavage, depending on the structure of the original molecule. These bodies, which are usually simpler in nature than those from which they have sprung, are called cleavage products, and without a doubt they are the primary products of the first step in organic decay. These compounds are subject to still further change, and because of the great number of agencies at work the secondary products that result may be simpler or more complex, according to conditions. Bacteria have a tendency, while tearing down organic matter, to construct certain built-up products which present a very complicated molecule until they are in turn degraded. The secondary products therefore vary widely because of differences in temperature, moisture, aeration, and other conditions.

The character of the secondary products probably exhibits a greater variation than does that of the original plant tissue. In the process of decay these products become black or brown in color, and are usually designated as humous materials in the soil. Organic matter, then, covers all the material of organic origin in the soil, and may refer not only to the original plant tissue, but also to that which has lost its identity in the secondary products. Humus refers specifically to the primary and the secondary products of decay, and may be simple or complex, according to conditions.

As the process of decay goes on, certain end products result. These are partially solid and partially gaseous. Carbon dioxide is a universal product of bacterial activity of all kinds, as is also water. Besides these, urea, ammonia, nitrites, and nitrates may result from nitrogenous decay. The three general classes of organic matter found in soil may be illustrated by the following diagram:

PLANT TISSUE	HUMUS	END PRODUCTS
[illegible]	[illegible]	[illegible]

Fig. 21.—Diagram illustrating the three general classes of organic matter found in soils.

It is therefore possible to have present, besides the original organic constituents which are mostly of plant origin, not only their primary and secondary degradation products, but also compounds either torn down or built up from these. An attempt to enumerate even the original compounds in the plant tissue, or even the simple end products of complete decay, would result in a huge list of materials representing almost every known class of organic compound. Such a procedure is possible, but is unnecessary as the important ones have already

been mentioned. It is to be kept in mind that the simpler products of decay are the ones utilized by crops, although it is a well-established fact that some of the secondary and intermediate compounds may be taken up by certain plants and probably are of some importance from the standpoint of use as plant-food.

91. **Composition of the soil humus.** — It is evident that the most complicated parts of the organic matter in the soil are the primary and the secondary products of decay, or the so-called soil humus. The study of this matter is difficult and calls for the very highest knowledge of organic chemistry. This is true for two reasons: first, because of the complexity of these compounds; and, secondly, because they are continually changing. A certain compound present in the soil one week may be altered the next week. Moreover, while some of the soil humus is soluble in water and may circulate in the soil solution, the bulk of it is insoluble. This in itself presents difficulties. When the soil humus is treated with the various extractive agents, reactions may be induced which would not take place in a normal soil. Compounds are then formed which not only would be abnormal, but would probably not exist under natural conditions.

A great many chemists have worked on the problem of the constitution of the organic matter of the soil and have published their results. The ideas of the early workers are really embodied in the conclusions advanced by Mulder,[1] who was in many ways far in advance of his

[1] Mulder, G. J. Die Organischen Bestandtheile im Boden. Chemie der Ackerkrume, I, pp. 308-360. Berlin, 1863. Also, Wiley, H. W. Agricultural Analysis, Vol. I, p. 53. Easton, Pa. 1906.

time. Mulder contended that the organic matter consisted of seven distinct compounds, as follows: —

1 and 2. Ulmic acid and ulmin 5. Geic acid
3 and 4. Humic acid and humin 6. Apocrenic acid
7. Crenic acid

These bodies he considered as arising from one another by oxidation; thus, ulmic acid ($C_{40}H_{28}O_{12}$) gave humic acid ($C_{40}H_{24}O_{12}$), which in turn yielded geic acid ($C_{40}H_{24}O_{14}$), followed by apocrenic acid ($C_{48}H_{12}O_{24}$), and finally by crenic acid ($C_{24}H_{12}O_{16}$). Such a classification seems very simple, but certain flaws are at once noticeable. In the first place, nitrogen does not find a place in any of these formulæ; secondly, the compounds are simpler than most plant tissue, which is not what would be expected, especially with some of the degradation compounds; thirdly, none of these products have united with the bases in the soil, a reaction that would be very likely to take place especially with acid compounds. Even the investigators[1] of Mulder's time obtained discordant results, but these were explained for the time being by assuming that the discrepancies occurred because of added molecules of water.

Later investigators, while progressing only slightly toward definite results, did accomplish one thing of importance, and that was throwing considerable doubt on the old ideas of the Mulder school of chemists. This again opened up the question as to the composition of the soil organic matter, especially the humus constituents. Thus, while it is evident that no such compounds as geic

[1] See Schreiner, O., and Shorey, E. C. The Isolation of Harmful Organic Substances from Soils. U. S. D. A., Bur. Soils, Bul. 53, pp. 15–16. 1909.

acid, humic acid, or crenic acid exist in the soil, one name has persisted in soil literature, that of humus and humic acid. The word humus, as already indicated, does not relate to any definite compound, but to the great mass of primary and secondary products of biological and chemical organic decay taking place in the soil. One of the men whose work established beyond a doubt the fact that humus was not a definite compound was Van Bemmelen.[1] His investigations still further showed that the soil humus was largely in a colloidal condition, and therefore exhibited properties quite distinct from those shown by crystalloids.

In recent years investigation has again been directed toward the immense field opened by the overthrow of the Mulderian school. Baumann,[2] by his researches, has shown freshly precipitated humus to possess properties which are largely colloidal in nature. Among these characteristics are high water capacity, great adsorptive power for certain salts, ready mixture with other colloids, power to decompose salts, great shrinkage on drying, and coagulation in the presence of electrolytes. Jodidi[3] has studied the composition of the acid-soluble organic nitrogen in peat and in mineral soils. The nitrogenous compounds thus obtained can be divided into the following groups: —

[1] Van Bemmelen, J. M. Die Absorptions Verbindungen und das Absorptionsvermögen der Ackererde. Landw. Versuchs. Stat., Band 35, Seite 67–136. 1888.

[2] Baumann, A. Untersuchungen über die Humussäuren. Mitt. d. K. bayr. Moorkulturanstalt, Heft 3, Seite 53–123. 1909.

[3] Jodidi, S. L. Organic Nitrogenous Compounds in Peat Soils I. Mich. Agri. Exp. Sta., Tech. Bul. 4, November, 1909. Also, The Chemical Nature of the Organic Nitrogen in Soil. Iowa Agr. Exp. Sta., Research Bul. 1, June, 1911.

1. Nitric nitrogen
2. Ammoniacal nitrogen
3. Diamino acids
4. Acid amides
5. Monamino acids

The two latter constituents were found to make up the bulk of the organic nitrogen, but quantitative determinations proved uncertain. These compounds produced ammonia readily, the rate depending on their chemical structure.

98. **The work of Oswald Schreiner.** — Of the chemists who have been most active and most successful, Schreiner[1] deserves especial mention. Our present knowledge of the chemical constitution of the organic matter of the soil is very largely due to his efforts. While he realized that the isolation of specific compounds from the soil was likely to present insurmountable problems, and that the identification of such compounds after they were obtained might be very difficult, he undertook a systematic extraction of the soil. As a result of several years of work he was able to isolate and identify a number of compounds. The complexity and varied character of these compounds is revealed by the following list of the more important bodies isolated: —

LIST OF COMPOUNDS ISOLATED FROM SOIL ORGANIC MATTER BY SCHREINER, SHOREY, SKINNER, REED, AND OTHERS, OF THE U. S. BUREAU OF SOILS

Hentriacontane, $C_{31}H_{64}$
Dihydroxystearic acid, $C_{18}H_{36}O_4$
Picoline carboxylic acid, $C_7H_7O_2N$
Histidine, $C_6H_9O_2N_3$

[1] Schreiner, O., and Shorey, E. C. The Isolation of Harmful Organic Substances from Soils. U. S. D. A., Bur. Soils, Bul. 53, 1909; also, Buls. 47, 70, 74, 77, 80, 83, 87, 88, and 90.

Monohydroxystearic acid, $C_{18}H_{36}O_3$
Agroceric acid, $C_{21}H_{42}O_3$
Agrosterol, $C_{26}H_{44}O \cdot H_2O$
Paraffinic acid, $C_{24}H_{48}O_2$
Lignoceric acid, $C_{24}H_{48}O_2$
Phytosterol, $C_{26}H_{44}O \cdot H_2O$
Pentosan, $C_5H_8O_4$
Oxalic acid, $C_2H_2O_4$
Succinic acid, $C_4H_6O_4$
Saccharic acid, $C_6H_{10}O_8$
Acrylic acid, $C_3H_4O_2$
Mannite, $C_6H_{14}O_6$
Rhamnose, $C_6H_{14}O_6$
Salicylic aldehyde, C_6H_4OHCOH
Arginine, $C_6H_{14}O_2N_4$
Cytosine, $C_4H_5ON_3 \cdot H_2O$
Xanthine, $C_5H_4O_2N_4$
Hypoxanthine, $C_5H_4ON_4$
Lysine, $C_6H_{14}O_2N_2$
Adenine, $C_5H_5N_5$
Choline, $C_5H_{15}O_2N$
Trimethylamine, C_3H_9N
Guanidine, CH_5N_3
Creatinine, $C_4H_7ON_3$
Creatine, $C_4H_9O_2N_3$
Nucleic acid (constitution unknown)
Trithiobenzaldehyde, $(C_6H_5CSH)_3$

From a chemical standpoint these compounds may be classified under four heads: (1) those containing carbon and hydrogen; (2) those containing carbon, hydrogen, and oxygen; (3) those containing carbon, hydrogen, and nitrogen, or carbon, hydrogen, oxygen, and nitrogen; (4) those containing sulfur in combination with the elements listed above. With the possible presence in soils of compounds containing five elements, it is of little wonder that the subject is a complicated one. It is evident, moreover, that the list given above is only a partial one, and many other compounds of an even more intricate composition will later be isolated.

So far as the plant is concerned, the compounds may be divided into three groups — those that are beneficial, those that are neutral, and those that are toxic, or harmful, in their effects. As an example of the first group,

histidine and creatinine[1] may be mentioned. Here is a case in which the compounds found in the soil humus may exert a stimulating effect on plant growth, and may also be a source of plant-food, supplementing the nitrates[2] to a certain extent. That the nitrogen of the soil organic matter may be utilized by plants is well summarized by the publications of Hutchinson and Miller.[3] As an example of a harmful compound arising from the decomposition of the organic matter, dihydroxystearic acid[4] may be mentioned as one of the best known. This compound was the first to be isolated and identified by Schreiner, and is very toxic.

93. Toxic material in the soil. – The discovery of such compounds in the soil has revived the old theory of toxicity,[5] by which the infertility of certain soils is accounted for. Root excretions are also held to be detrimental to succeeding crops of the same kind. The

[1] Skinner, J. J. Effect of Histidine and Arginine as Soil Constituents. Eighth Internat. Cong. App. Chem., Vol. XV, pp. 253–264. 1912. Also, Beneficial Effects of Creatinine and Creatine on Growth. Bot. Gaz., Vol. 54, No. 2, pp. 152–163. 1912.

[2] Schreiner, O., and Skinner, J. J. Nitrogenous Soil Constituents and Their Bearing upon Soil Fertility. U. S. D. A., Bur. Soils, Bul. 87, p. 68. 1912. Also, Schreiner, O., and others. A Beneficial Organic Constituent of Soils; Creatinine. U. S. D. A., Bur. Soils, Bul. 83, p. 44. 1911.

[3] Hutchinson, H. B., and Miller, N. H. J. The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants. Jour. Agr. Sci., Vol. 4, Part 3, pp. 282–302. 1912.

[4] Schreiner, O., and Skinner, J. J. Some Effects of a Harmful Organic Soil Constituent. U. S. D. A., Bur. Soils, Bul. 70. 1910.

[5] See Schreiner, O., and Reed, H. S. Some Factors Influencing Soil Fertility. U. S. D. A., Bur. Soils, Bul. 40, pp. 35–40. 1907.

toxic materials of the soil humus largely originate under conditions of poor drainage and aëration, and consequently are biological in their genesis. The toxicity of such compounds as dihydroxystearic acid, picoline carboxylic acid,[1] and aldehydes[2] may therefore be overcome by oxidation,[3] so that good soil aëration is a factor in dealing with such conditions. Insufficient sanitation of the soil seems to account very largely for the presence of soil toxins. Fertilizers, according to Schreiner and Skinner,[4] seem to decrease the harmful effects of such compounds; nitrogenous fertilizers overcoming some toxic materials, and phosphorus or potash neutralizing others. For example, in water solution and sand culture, nitrogen seems especially efficacious in correcting such toxic substances as dihydroxystearic acid and vanillin, phosphorus is particularly powerful in counteracting cumarine, and potash has considerable influence on quinone.

While the real importance of the toxic material generated in the soil cannot be fully discussed at this point, it is quite evident that such constituents do tend to develop under insanitary conditions and must be considered in

[1] Schreiner, O., and Shorey, E. C. The Isolation of Harmful Organic Substances from Soils. U. S. D. A., Bur. Soils, Bul. 53, pp. 46-49. 1909.

[2] Schreiner, O., and Skinner, J. J. Harmful Effects of Aldehydes in Soils. U. S. D. A., Bul. 108 (Professional Paper). 1914.

[3] Schreiner, O., and others. Certain Organic Constituents of Soils in Relation to Soil Fertility. U. S. D. A., Bur. Soils, Bul. 47, p. 52. 1907. Also, Schreiner, O., and Reed, H. S. The Rôle of Oxidation in Soil Fertility. U. S. D. A., Bur. Soils, Bul. 56, p. 52. 1909.

[4] Schreiner, O., and Skinner, J. J. Organic Compounds and Fertilizer Action. U. S. D. A., Bur. Soils, Bul. 77. 1911.

the discussion of the composition of that great group of intermediate compounds, called humus, arising from the decay of the organic matter of the soil. While Schreiner found twenty soils, out of a group of sixty taken in eleven States of this country, to contain dihydroxystearic acid, this does not necessarily mean that this compound in itself is a serious detrimental factor. It is very likely that such compounds are merely products of improper soil conditions, and are to be considered as concomitant with depressed crop yields. When such conditions are righted, the so-called toxic matter will disappear. Good drainage, lime, tillage, a balanced food ration, promoted aëration and oxidation, are so efficacious in this regard that permanent soil toxicity need never be feared by the farmer.

94. End products of humus decay. As the processes of chemical and biological decay of the soil organic matter proceed, the simple compounds already noted begin to appear. This change is of course coördinate with a certain amount of synthetic action, but compounds thus built up must ultimately succumb to the agencies at work and suffer a splitting-up and reduction to simple bodies. Carbon dioxide is one of the most important of these compounds, being always a product of bacterial activity. Its importance has already been noted in the discussion of weathering. Here it heightens the solvent power of water and tends to increase the amount of plant-food carried in the soil solution. Carbonation is a direct result of its presence. Carbon dioxide may also tend to flocculate colloidal matter in soils, and thus benefit the physical conditions. With increased organic matter in any soil, there greater bacterial action and an increase in the carbon dioxide evolved may well be expected. In

fact, the carbon dioxide production of a soil is considered by some authors[1] to be a measure of bacterial activity. With this increase in carbon dioxide the soil air becomes more heavily charged and an alteration in bacterial and plant relationships may thereby be induced. The following figures, by Wollny,[2] show the composition of the soil atmosphere and the effects of additional humous material on the carbon dioxide content:

	Percentage by Volume of	
	CO_2	O
Soil air (average of 19 analyses)	3.64	18.22
Atmospheric air	.04	20.96
A sandy soil	1.06	19.72
A sandy soil plus manure	9.74	10.35

While carbon dioxide may be evolved by the splitting-up of both carbohydrate and nitrogenous bodies, ammonia results only from the latter. It is really the first extremely simple nitrogenous body produced. It can be utilized by some plants as a source of nitrogen, as is also true with certain simple humic bodies, but ordinarily it must undergo oxidation. This oxidation results in nitrites (NO_2) and ultimately in nitrates (NO_3), the latter being usually considered as the chief source of the nitrogen utilized by plants.

[1] Stoklasa, J., and Ernest, A. Ueber den Ursprung, die Menge, und die Bedeutung des Kohlendioxyds im Boden. Centrlb. Bakt., II, 14, Seite 723-736. 1905.

[2] Wollny, E. Die Zersetzung der Organischen Stoffe, Seite 2. Heidelberg, 1897.

Other end products, such as methane (CH_4), hydrogen disulfide (H_2S), free nitrogen (N), sulfur dioxide (SO_2), carbon disulfide (CS_2), and the like, may also result. They are relatively unimportant, however, as regards the plant, in comparison to the rôle played by carbon dioxide, ammonia, the nitrites, and the nitrates. The production of the nitrates from ammonia particularly is very clearly correlated with good soil conditions, especially optimum moisture and adequate aëration. The proper handling of the soil, then, not only will tend to eliminate toxic matter and prevent its further formation, but will encourage the proper decay of the soil humus and the production of end products which will function directly or indirectly as plant foods.

Snyder[1] found that when humus was extracted with an alkali and then precipitated with an acid, it yielded from five to twenty-five per cent of a reddish brown ash. This ash contained silica, iron, and alumina, as well as magnesia, potash, phosphorus, sulfur, sodium, and calcium. While part of these mineral constituents may be chemically combined with humus, it is probable that some may be present because of the adsorptive capacity of the organic colloids which are always present in humus generated under normal conditions. Snyder has estimated that in an ordinary soil containing a fair amount of organic matter, one-sixth of the phosphorus and one-twelfth of the potash may be present in such a state. They are thus fairly available, and are yielded much more readily to the plant than if of a strictly inorganic nature.

95. Carbonized materials of soil. — After the extraction of the soil for the study of the ordinary humus com-

[1] Snyder, Harry. Production of Humus from Manures. Minnesota Agr. Exp. Sta., Bul. 53, pp. 29–30. 1897.

pounds, a considerable mass of material remains, which is insoluble in water, alkali, and other ordinary solvents. By the extraction of a large amount of soil, Schreiner[1] was able to study this material. He found it susceptible to division into six groups, as follows: (1) plant tissue, (2) insect and other organised material, (3) charcoal particles, (4) lignite, (5) coal particles, and (6) materials resembling natural hydrocarbons, as bitumen, asphalt, and the like. Such material was found not only near the surface of the soil, but at depths of fifteen or twenty feet below. All the groups above listed were found by Schreiner to be represented in the thirty-four soils collected from all parts of the United States and subjected to rigid test.

The exact origin of such material is problematical. Forest and prairie fires, infiltration, mild oxidation, and lignification might be mentioned. Of a certainty, the agencies of distribution are the natural forces engaged in physical weathering. This carbonised material is important, as it makes up no inconsiderable part of the soil humus. It is very resistant, and consequently lends stability to the soil organic matter. It can be divided into two general groups, organised and unorganised; in the former the original structure remains intact, while in the latter the original features have been obliterated. The study of such material and the changes that it undergoes not only increases the list of known organic compounds existing in the soil, but throws considerable light on the nature of the soil organic matter as a whole.

96. The estimation of the soil organic matter. — Many methods have been proposed for the determination

[1] Schreiner, O., and Brown, B. E. Occurrence and Nature of Carbonized Material in Soils. U. S. D. A., Bur. Soils, Bul. 90. 1912.

of the organic matter in soils, but none have proved entirely satisfactory, since the composition of this material is so complicated and so likely to change while under investigation. Other soil constituents also tend to interfere with the determination. Two general methods seem worthy of mention, as they have been used very widely in soil analyses and at least give comparative, if not absolutely accurate, results.

Loss on ignition.[1] This is a simple method which designs to burn off the organic matter and determine its loss by difference. Five grams of dry soil are placed in a platinum dish and ignited at a low red heat until the organic matter is all oxidized. The cold mass is moistened with ammonium carbonate and heated to a temperature of 150° C. in order to expel the excess of ammonia. The loss is rated as organic matter.

This method is open to the objection that, besides the loss of organic matter, a certain small amount of water of combination, together with all ammoniacal compounds, nitrates, all carbon dioxide, and some alkali chlorides if the temperature is carried too high, is driven off. The method therefore gives high results, especially in the presence of large amounts of hydrated silicates. An attempt to replace the carbon dioxide is made in the treatment of the cold mass with ammonium carbonate. Notwithstanding these objections, this method is one of the best and is very generally used all over the world in estimating the organic matter of the soil. Very often

[1] Huston, H. A., and McBride, F. W. A Modification of Grandeau's Method for the Determination of Humus. U. S. D. A., Div. Chem., Bul. 38 (edited by H. W. Wiley), pp. 84–92. 1893.

the combustion is carried on in a current of oxygen over hot copper oxide. The organic carbon may thus be determined very accurately, and the organic matter calculated by multiplying the carbon found by the factor 1.724.

Chromic acid method.[1]—This method, proposed by Wolff, has been modified and improved by various chemists. Warington and Peake[2] have perhaps done more with the method than any other investigators. In the United States the modification of Cameron and Breazeale[3] has been very generally accepted. It consists in the treatment of the soil sample with sulfuric acid and chromic acid or potassium bichromate. The organic matter, in the presence of the sulfuric acid and an oxidizing agent, evolves carbon dioxide until, if the mixture is boiled, practically all of the carbon is thus driven off. This gas is drawn through a train of absorption bulbs, caught in a solution of potassium hydrate, and thus weighed. On the supposition that organic matter is 58 per cent carbon, it is very easy to make the calculation. The carbon found may be multiplied by 1.724, or the carbon dioxide by .471. The product is considered as soil organic matter. The results thus obtained are usually lower than with combustion or ignition methods,

[1] For comparison of methods, see Wiley, H. W. Principles and Practices of Agricultural Analysis, Vol. I, pp. 347-356. Easton, Pa. 1906.

[2] Warington, R., and Peake, W. A. On the Determination of Carbon in Soils. Jour. Chem. Soc. (London) Trans., Vol. 37, pp. 617-625. 1880.

[3] Briggs, L. J., and others. The Centrifugal Method of Mechanical Soil Analysis. U. S. D. A., Bur. Soils, Bul. 24, pp. 33-38. 1904. Also, Cameron, F. K., and Breazeale, J. F. The Organic Matter in Soils and Subsoils. Jour. Amer. Chem. Soc., Vol. 26, pp. 29-45. 1904.

due to the resistance to oxidation[1] by the carbonized matter, already discussed. This material, while it succumbs to ignition, resists the action of the sulfuric and chromic acids to a very large degree.

97. **The estimation of soil humus.** — The common method of humus estimation is that proposed by Grandeau.[2] The sample of soil is first washed with acid in order to remove all bases. It is next treated with ammonia, which will then dissolve out the humous materials. By catching this percolate, evaporating it to dryness, and weighing it, the percentage of humus may be calculated. The dark humous extract obtained with the ammonia is called the Matière Noire.

This method has undergone several modifications,[3] of which that of Hilgard[4] and that of Houston and McBride[5] seem the most promising. The method of the latter chemists has been adopted by the Association of Official Agricultural Chemists and is considered as the official method. In the procedure an attempt is made to keep the concentration of the ammonia in contact with the soil constant during the extraction. Consequently the sample, after treatment with the acid, is washed into a

[1] Schreiner, O., and Brown, B. E. Occurrence and Nature of Carbonized Material in Soils. U. S. D. A., Bur. Soils, Bul. 90, pp. 19-24. 1912.

[2] Grandeau, L. Traité d'Analyse des Matières agricoles. I, p. 151. 1897.

[3] A comparison of the various methods is found as follows: Alway, F. J., and others. The Determination of Humus. Nebr. Agr. Exp. Sta., Bul. 115. June, 1910.

[4] Hilgard, E. W. Humus Determination in Soils. U. S. D. A., Div. Chem., Bul. 38 (edited by H. W. Wiley), p. 80. 1893.

[5] Wiley, H. W. Official and Provisional Methods of Analysis. U. S. D. A., Bur. Chem., Bul. 107, p. 19. 1908.

500 cubic centimeter flask, which is filled to the mark with 4 per cent ammonia. Digestion is allowed to proceed for twenty-four hours, with frequent shakings, and and an aliquot portion of the supernatant liquid is taken for analysis. This method with its modifications is practically the only one that we have for the estimation of soil humus. It is based on the fact that when a soil is lacking in active basic material, the humous matter may be extracted with ammonia. A modification of this method may be used as a test for soil acidity, as any soil of humid regions allowing the extraction of humus by ammonia alone must lack basic materials.

The composition of the ash constituents of the matière noire is given by Snyder[1] as follows, the data being the average of eight analyses :—

THE ASH FROM THE HUMUS OF MINNESOTA PRAIRIE SOILS

	Percentage
Insoluble	61.97
Fe_2O_3	3.12
Al_2O_3	3.48
K_2O	7.50
Na_2O	8.17
CaO	.09
MgO	.36
P_2O_5	12.37
SO_3	.98
CO_2	1.64

The relatively high percentage of phosphoric acid is immediately noticeable in this analysis. This indicates

[1] Snyder, Harry. Soils. Minnesota Agr. Exp. Sta., Bul. 41, p. 30. 1895.

that no mean portion of the soil phosphates is held in organic combination. The promotion of favorable humous decay must thus liberate a considerable amount of phosphorus for plant utilization.

98. **Organic content of representative soils.** The organic content of soils varies widely according to climatic conditions. The following average data show the limits of variation as well as the comparative content of the important soil sections of the United States: —

ORGANIC CONTENT OF UNITED STATES SOILS

	Sandy Soils		Clay Loams and Loams	
	Soil	Subsoil	Soil	Subsoil
North Central States .	1.84	.78	3.06	1.07
Northeastern States .	1.66	.60	3.72	1.35
South Central States .	1.16	.55	1.69	.85
Southeastern States .	.93	.43	1.53	.73
Semiarid States . . .	.99	.02	2.04	1.11
Arid States	.89	.04	1.03	.12

It is at once apparent that the subsoil contains considerably less organic matter than do the surface layers. Also, the areas of the United States that have been glaciated are noticeably richer in organic material than the residual, coastal plain, and arid regions. This is largely a climatic and geochemical relationship. Some soils, particularly alluvial soils, very often run higher than the average data given above. An organic content of 5 or 6 per cent is not an uncommon figure with such materials. Muck and peat soils are of course not to be classified with the above, as their organic content may

range from 35 to 85 per cent, according to the admixture of mineral matter from extraneous sources.

98. **The humus content of soils.** — The humus content of soils is of course lower than the organic matter therein contained. It likewise varies according to climate and region, not only in amount, but also in composition. The following data, compiled from Hilgard,[1] illustrate this point: —

THE HUMUS OF ARID AND HUMID SOILS

	Humus in Soil (Percentage)	Nitrogen in Humus (Percentage)	Nitrogen in Soil (Percentage)
61 Arid upland soils	.91	15.23	.135
10 Subirrigated arid soils	1.06	8.38	.089
24 Humid soils	4.58	4.23	.165

It is evident that humid soils not only contain the greatest amounts of organic matter, but also excel in humus. The humus of the arid regions, however, is richer in nitrogen, due to the peculiar decomposition going on. As a consequence the nitrogen in the soil of humid regions is not greatly in excess of that in the soils of drier climates.

The percentage of humus not only decreases as the lower depths of soil are examined, but also changes in composition, becoming poorer in nitrogen the deeper the soil is penetrated. The following data on a Russian river soil, quoted by Hilgard,[2] may be cited as an instance: —

[1] Hilgard, E. W. Soils, pp. 136-137. New York. 1911.
[2] Ibid., p. 138.

The Humus of a Russian Alluvial Soil

Depth in Feet	Percentage of Humus	Percentage of Nitrogen in Humus	Percentage of Humus Nitrogen in Soil
1	4.24	5.30	.064
2	4.16	4.82	.054
3	4.14	3.82	.044
4	4.17	3.78	.044
5	.24	2.18	.018
6	.60	2.66	.016
7	.47	2.64	.012
8	.28	3.54	.012
9	.54	2.24	.012
10	.58	1.15	.006
11	.53	1.51	.008
12	.44	1.81	.008

Other depth relationships, especially regarding the proportions of carbon, humus, and nitrogen, are brought out in the following data, obtained by Alway and Vail[1] in the study of Nebraska Soils:—

Composition of a Nance County, Nebraska, Soil near Genoa

Depth in Feet	Percentage of Nitrogen	Percentage of Carbon	Percentage of Humus	Percentage of N in Humus	Ratio of $\frac{C}{N}$	$\frac{H}{N}$	$\frac{C}{H}$
1	.265	2.61	2.47	1.61	10.8	9.7	1.1
2	.102	.85	1.00	.90	8.3	9.8	.9
3	.056	.31	.40	.52	5.5	7.1	.8
4	.043	.24	.30	.64	5.7	7.1	.8
5	.034	.17	.19	.33	5.0	5.6	.9
6	.027	.14	.16	.36	5.2	5.9	.9

[1] Alway, F. J., and Vail, C. E. The Relative Amounts of Nitrogen, Carbon, and Humus in Some Nebraska Soils. Nebraska Agr. Exp. Sta., 25th Ann. Rept., p. 155. 1912.

100. Influence of the original material on the resultant humus. — It is evident that the source from which any humus material is derived will exert a profound influence on its composition, especially its nitrogen content. Snyder[1] has investigated this by mixing certain materials with a soil poor in humus and allowing the process of decay to proceed for a year under favorable conditions. At the end of the period the humus was extracted by the Grandeau method. The results are given below: —

THE COMPOSITION OF HUMUS PRODUCED FROM VARIOUS ORGANIC MATERIALS

	C	H	O	N
Sugar	57.84	3.04	39.04	.06
Sawdust	49.28	3.33	47.07	.32
Oats straw	54.30	2.48	40.72	2.50
Wheat flour	51.03	3.82	40.14	5.02
Cow manure	41.95	6.26	45.03	6.16
Green clover	54.22	3.40	34.14	8.24
Meat scrap	48.77	4.20	36.07	10.96

Although the humification may not have reached completion in this case, the great variation in nitrogen is striking. Existing, as it probably does, mostly as acid amides and monamino acids, it will change readily to ammonia and exert a marked effect on plant growth. Possibly the variation of the nitrogen in soil humus is the most potent factor in the nutritive functionings of this material. The variability of the carbon, hydrogen, and oxygen of the soil humus is not such an important factor, as these elements can easily be supplied to the

[1] Snyder, Harry. Production of Humus from Manures. Minnesota Agr. Exp. Sta., Bul. 53, p. 25. 1897.

soil by the plowing-under of green materials or of barnyard manures. In general, the percentage content of inorganic matter increases as the organic matter decays.

101. Effects of organic matter on soil. — The effects of the organic matter on soil and plant conditions are as numerous as they are complex. Some of the influences are direct, others are indirect. As the specific gravity of organic matter is low, the first effect of its addition would be to lower the absolute and the apparent specific gravity of the soil. As the water capacity of humus is very high, a soil rich in organic constituents usually possesses a high water-holding power. This makes possible greater volume changes both on drying and in the presence of excessive moisture. The granulating effects of wetting and drying and freezing and thawing are therefore accelerated. The organic matter tends also to spread the individual particles of soil farther apart, especially in a clay. Its loosening effects are immediately apparent in such soil. On the other hand, because organic matter has a higher cohesive and adhesive power than sand, it performs the function of a binding material with the latter soil, a condition much to be desired in a material possessing such textural characteristics.

The better tilth induced by the presence of organic matter in any soil tends to facilitate ease in drainage and to encourage good aëration. These two conditions are of course necessary for the promotion of soil sanitation. Root extension and bacterial activity are thus increased. It is of especial importance that the splitting-up of the organic matter shall take place in the presence of plenty of oxygen, in order that toxic compounds may not be generated and that a humus highly favorable to plant growth shall be produced. The increased water

capacity of the soil resulting from the presence of organic materials is of some importance in drought resistance, while the black color imparted by the humus tends to raise the absorptive power of the soil for heat.

The soil organic matter, however, functions in other ways than those strictly physical. The humus or its degradation products may serve as plant-food. Bacteria and other soil organisms are also furnished a source of energy thereby, and the production of carbon dioxide is much increased. This carbon dioxide, as well as the organic acids generated, tends to raise the capacity of the soil water as a solvent agent, and thus the amount of mineral plant-food available to the crop is greatly increased. The general effect of organic matter, then, is to better the soil as a foothold for plants, and to increase either directly or indirectly the available food supply for the crop.

103. Maintenance of soil organic matter. — The maintenance of a proper supply of organic matter in a soil is a question of great practical importance, as productivity is governed very largely by the humus content of the soil. This maintenance of the soil humus depends on two factors — the source of supply and methods of addition, and the promotion of proper soil conditions in order that the organic matter may perform its legitimate functions.

The organic matter of the soil may be increased in a natural way by the plowing-under of green crops. This is called *green-manuring* and is a very satisfactory practice. Such crops as rye, buckwheat, clover, peas, beans, and vetch lend themselves to this method of soil improvement. Not only do these crops increase the actual carbohydrate content of a soil, but in the case of legumes the nitrogen also is increased in amount, due to the

symbiotic action of the nodule bacteria. Green-manure crops may also protect the soil from loss of plant-food by leaching. The addition of barnyard manure is a common method of raising the organic content from external sources, and on decaying this manure performs the same function as natural soil humus. Muck, peat, straw, or leaves may be used in a similar manner.

Improper soil conditions not only prevent the proper decay of organic matter, but also tend to encourage the production of products inimical to plant growth. Therefore, in order that organic materials added to any soil may produce the proper humous constituents and perform their normal functions, soil conditions in general must be of the best. Tile drainage should be installed, if necessary, in order to promote aëration and granulation. Lime should be added if basic materials are lacking, for it promotes bacterial activity as well as plant growth. The addition of fertilizers will often be a benefit, as will also the establishment of a suitable rotation. The rotation of crops not only prevents the accumulation of toxic materials, but also, by increasing crop growth, makes possible a larger addition of organic matter by green-manuring.

Good soil management seeks to adjust the addition of organic matter, the soil conditions, and the losses through cropping and leaching, in such a way that paying crops may be harvested without impairing the humus supply of the soil. Any system of agriculture that tends to permanently lower the organic matter of the soil is impractical, and improvident, as well as unscientific.

CHAPTER IX

THE COLLOIDAL MATTER OF SOILS[1]

It has already been noted, in the discussion of the clay separate of any soil, that in the presence of water certain of the very finest particles, even though apparently dissolved, assume particular and important properties, such as high adsorption, nondiffusion through membranes, and the Brownian movement. Such material has been designated as colloidal in nature. It must be understood from the beginning, however, that

[1] Some of the following general references may prove of interest: —

Freundlich, H. Kapillarchemie. Leipzig, 1909.

Zsigmondy, R. Kolloidchemie. Leipzig, 1912.

Bancroft, W. D. The Theory of Colloid Chemistry. Jour. Phys. Chem., Vol. 18, No. 7, pp. 549–558. 1914.

Niklas, H. Die Kolloidchemie und ihre Bedeutung für Bodenkunde, Geologie, und Mineralogie. Internat. Mitt. für Bodenkunde, Band II, Heft 5, Seite 383–408. 1912.

Ramann, E. Kolloidstudien bei Bodenkundlichen Arbeiten. Kolloidchemische Beihefte, Band II, Heft 8/9, Seite 285–298. 1911.

König, J., Hasenbäumer, J., und Hassler, C. Bestimmung der Kolloide im Ackerboden. Landw. Ver. Stat., Band 75, Heft 5/6, Seite 377–441. 1912.

Noyes, A. A. The Preparation and Properties of Colloidal Mixtures. Jour. Amer. Chem. Soc., Vol. 27, pp. 85–104. 1905.

Thaer, W. Der Einfluss von Kalk und Humus auf die Mechanische und Physikalische Beschaffenheit von Ton-, Lehm-, und Sandböden. Jour. f. Landw., Band 58, Heft 1, Seite 9–52. 1910. Also, Kolloidchemische Studien. Jour. f. Landw., Band 60, Heft 1, Seite 1–18. 1912.

colloidal material does not differ from crystalloidal in chemical composition, but the distinction is merely one of size of particles. For example, if large particles are suspended in water, they will immediately sink, since their weight is so much greater than the surface that is exposed for buoyance. When these particles are decreased in size, their weight decreases much faster than the surface exposed. It is therefore evident that a point will at last be reached at which the particles, because of their minute size, will form a homogeneous solution. The upper limit of the colloidal state has then been entered.

103. **The colloidal state.** — The colloidal state in which these particles are now found is a peculiar one, and exhibits much diversity, not only in properties, but also in the size of particle in which the material exists. The upper limit of the clay group as designated by the classification of the United States Bureau of Soils is .005 millimeter, while the upper limit of the particle existing in a colloidal state is estimated to be below .005 of a micron, or .000005 millimeter. Indeed, so small are the colloidal particles that they become molecular complexes, that is, a few molecules may go to make up a particle. The various colloids, or the same colloid under different conditions, may exhibit greatly differing sizes of particles. Some colloidal particles are very large, approaching the upper limit already set for material in such a state. Other particles are finer. It is evident that a gradation must exist until a particle is reached which consists of only one molecule. The solution then ceases to be a molecular complex and becomes a true solution. The colloidal state thus grades into the true solution, just as an ordinary suspension grades into a true, or colloidal,

suspension. While this method of comparison fails to recognize the various phases that colloidal materials may exhibit and is therefore faulty in this regard, it does lay emphasis on the differences as to size of particle that exist between colloidal bodies and materials as they are ordinarily recognized. This relationship is shown by the following diagram: —

ORDINARY SUSPENSION | COLLOIDAL STATE | TRUE SOLUTION

MOLECULAR DISPERSION

FIG. 22. — Diagram showing the relationship of the colloidal state (molecularly dispersed) to ordinary suspensions and true solutions.

Since colloidal particles vary in size from .005 of a micron to a molecule, the range must be very great. Just how great cannot be very accurately stated. It is interesting to note, however, that this range is much greater in proportion than is exhibited between the fine gravel and the ordinary clay particles found in soil. With this possible difference, it is no great wonder that the various colloids exhibit with different intensities the characteristics so peculiar to them and of such great importance in everyday life. The particles in the upper range of the colloidal field can be seen with the ordinary microscope. As such particles become smaller they cease to be visible under the ordinary microscope and can be detected only by the ultramicroscope. It is probably true that by far the greater proportion of the particles of material in a colloidal state cannot be detected by microscopic means. This gradation of colloidal materials and the extreme fineness of the particles is well illustrated by the following diagram (Fig. 23), although it fails to convey any idea regarding the various phases that colloids may occupy.

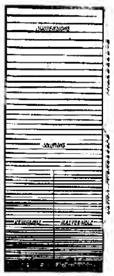

FIG. 33. — Diagram showing the possible range in the size of colloidal particles.

104. The properties of colloids. — In general there are certain properties which materials in a colloidal state exhibit and by which they are distinguished from true solutions. In the first place, since they are not in true solution they exert little effect on the freezing point, on vapor tension, and on vapor pressure. Some colloids have absolutely no effect on these conditions, while others, as they allow a certain small amount of true solution to take place, do possess such

influences to a slight degree. Secondly, colloids do not pass readily through semipermeable membranes, as parchment paper, while crystalloids do. This serves as a very easy way of separating colloidal and crystalloidal material. As a matter of fact, the membrane is itself a colloid. Thirdly, heat and the addition of electrolytes will serve to coagulate or precipitate certain colloids, a property which again serves to distinguish them sharply from a true solution. Fourthly, colloidal material has great adsorptive power, not only for water, but also for materials in solution, a quality of extreme importance in soil studies.

It has been shown that a colloid is a material in a certain state of division, in which it exhibits properties not possessed by an ordinary suspension or by a true solution. It is therefore proper to speak of matter so divided as being in the colloidal state, or colloidal condition. It is not to be inferred, because the colloidal phase is contrasted with the crystalloidal, that colloids are amorphous. They may or may not be in such a condition. Moreover, the same material may exist without chemical change either in the colloidal or non-colloidal state. For example, silicic acid, ferric hydrate, gold, carbon black, and other materials, may or may not be colloidal, according to circumstances. The fineness of division is the explanation of colloidal properties. In order to place such a discussion on a more understandable basis, a few illustrations of the colloidal state will not be amiss. The following materials, which may exist as colloids, may be for convenience grouped under two general heads, organic and inorganic: —

Organic: Gelatin, agar, caramel, albumin, starch, jelly, humus, carbon black, tannic acid, etc.

Inorganic: Gold, silver, iron, ferric hydrate, aluminum oxide, zinc oxide, silver iodide, Prussian blue, etc.

106. Colloidal phases. — In general, two conditions are necessary for the colloidal state — a dispersive medium, and a material that will disperse, the latter being usually designated as the disperse phase. Three materials may function as a dispersive medium — a liquid, a solid, or a gas. In the same way, with each dispersive medium there may be three disperse phases — a liquid, a solid, or a gas. This gives nine general phases to be considered in colloidal chemistry. From the soil standpoint, the liquid-solid and the liquid-liquid phases are by far the most important and will be the only ones to receive detailed attention here. In the liquid-solid phase, as with colloidal gold or ferric hydrate, the particles are suspended in water as the dispersive medium. In the case of gelatin, another liquid-solid example, the jelly surrounds the dispersive medium, or liquid. An emulsion may exhibit the liquid-liquid phase, and possibly exists in soils rich in humus.

In these colloidal phases under discussion and of such particular interest in soil study, two general classes of materials are found, which seem to differ radically from each other and yet are likely to lead to considerable confusion unless special pains are taken to distinguish between them. As types, gelatin and a colloidal suspension of ferric hydrate may be cited. The gelatin is considerably more viscous than water, while the ferric hydrate does not differ from water in this respect. The former gelatinizes on cooling or on loss of moisture, but will become dispersed again on the addition or presence of water. In other words, it will pass again and again, back and forth,

from a sol to a gel. It is what might be called a reversible colloid. Moreover, it is not coagulated by ordinary additions of salt or by heating. The ferric hydrate colloid, on the other hand, when precipitated or agglutinated by any means may not easily be brought back again to the sol state. It is a so-called irreversible colloid. Moreover, it is thrown down by the addition of electrolytes. There exist, then, the viscous, gelatinizing, reversible colloids, and the non-viscous, non-gelatinizing, easily coagulable, and non-reversible colloids, besides all gradations and variations between the two. In the ordinary clay soil, both types of these materials probably exist and play important parts in the physical and chemical characteristics exhibited.

106. Flocculation. – While the gelatinous colloids of the soil, such as some of the humic materials, are not agglutinated by the addition of electrolytes, most of the colloids of a nature similar to colloidal silicic acid and ferric hydrate are thrown down by this treatment. This phenomenon is often spoken of as flocculation. A very good example is afforded by treating a clay suspension with a little caustic lime. The tiny particles almost immediately coalesce into floccules, and, because of their combined weight, sink to the bottom of the containing vessel, leaving the supernatant liquid clear. The same action will take place in the soil itself, but of course with less rapidity and under conditions less noticeable to the eye. The colloids thus thrown down, being largely irreversible, cannot again assume their former attributes and thus lose their distinguishing characteristics. In general, acids bring about flocculation while alkalies do not, calcium oxide and calcium hydrate being the best-known exceptions to the latter. Ammonia is an intense deflocculator.

Just how this phenomenon of flocculation or agglutination may be accounted for theoretically it is rather difficult to state. The general theory is one of electrification. It is found that certain colloids, when subjected to the proper electric current, will migrate to either the positive (anode) or the negative (cathode) pole. These particles evidently carry a charge of electricity. Ferric hydrate, aluminium hydrate, and basic dyes, for example, move toward the cathode and carry a positive charge; while arsenious sulfide, silicic acid, gold, silver, and acid dyes move toward the anode and are negative. It is assumed that as long as the colloidal particles remain charged they repel each other and the colloidal state persists. When an electrolyte is added the ionization is supposed to cause a discharge of the repellent electricity carried by the colloidal particles, and flocculation or agglutination immediately takes place.

Certain colloids may flocculate certain others, as the gelatinization of silicic acid by ferric hydrate. At times one colloid may protect another, probably by surrounding it with a protective film. Such a case may be shown by adding gelatin to a clay suspension. When a colloid such as ferric hydrate is flocculated, it loses to a certain extent its peculiar properties, and assumes the characteristics of ordinary materials. It is evident, therefore, that if the properties exhibited by colloidal materials become either directly or indirectly detrimental to plants, their flocculation would be beneficial. In field practice this is usually accomplished by the addition of lime. The colloidal material existing in a normal soil and possessing a gelatinous nature, similar in general to gelatin, is probably not all flocculated by the addition of ordinary amounts of electrolytes. This material may be influenced by

drying, whereby it slowly gives off water, becomes more and more viscous, and at last may lose its gel qualities and become hard and irreversible. It is evident, therefore, that wetting and drying, frost, and the like, become factors in dealing with this form of colloidal matter.

107. Common soil colloids and their generation.[1]—The common soil colloids may, for convenience, be discussed under two heads, organic and inorganic. Of the former, the so-called humic acid stands as the example; of the latter, silicic acid, ferric hydrate, and amorphous zeolitic silicates are the commonest.

Organic colloids.—The humic colloids in a normal fertile soil probably make up the bulk of the colloidal matter. Such material is very heterogeneous, very complex, and constantly changing. As yet very little study of the organic soil colloids has been made because of the difficulties presented by the problem. Humic colloids may be viscous or non-viscous, as the case may be, and may or may not be thrown down by lime. The adsorptive power of these colloids for water, gases, and such materials as calcium, magnesium, and potash, is

[1] Van Bemmelen, J. M. Die Absorption. Seite 114-115. Dresden, 1910. Also, Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde. Landw. Ver. Stat., Band 35, Seite 69-136. 1888.

Way, J. T. On Deposits of Soluble or Gelatinous Silica in the Lower Beds of the Chalk Formation. Jour. Chem. Soc., Vol. 6, pp. 102-106. 1854.

Warington, R. On the Part Taken by Oxide of Iron and Alumina in the Adsorptive Action of Soils. Jour. Chem. Soc., 2d ser., Vol. 6, pp. 1-19. 1868.

Cushman, A. S. The Colloid Theory of Plasticity. Trans. Amer. Cer. Soc., Vol. 6, pp. 65-78. 1904.

Ashley, H. E. The Colloid Matter of Clay and its Measurement. U. S. Geol. Sur., Bul. 388. 1909.

very highly developed — more so, probably, than that of the inorganic colloids. These organic colloids are formed during the tearing-down and splitting-off processes of bacterial activity. Some of the humic materials are thrown off in a sufficiently fine state of division to assume the condition that has been designated as colloidal. Of course the chemical forces of weathering are also operative in this process of organic colloidal production.

Mineral colloids. — The inorganic soil colloids, especially ferric oxide and silicic acid, are less complex than the organic and have been more thoroughly studied. Such colloids are generated during the operation of the ordinary forces of weathering, especially the chemical phase. For example, when a feldspar undergoes decomposition, the following reaction may be used to illustrate the possible change that takes place: —

$$2\,KAlSi_3O_8 + 2\,H_2O + CO_2 = H_4Al_2Si_2O_9 + 4\,SiO_2 + K_2CO_3$$

Kaolin practically always has its origin in this way, together with an alkali carbonate and silica. The process is essentially one of hydration and carbonation; the CO_2 by reacting with the alkali permits the process to go on. The silica may go in three directions, according to conditions — to free quartz, to hydrated silicates, and to colloidal silica. Similar reactions may be written for iron and aluminium, but they can only show, as does the above, the general trend of the change. In general it can be concluded that most inorganic colloids arise from ordinary chemical weathering, together with secondary minerals of various kinds. Such colloids must be very dilute and are difficult to study because of their reaction among themselves.

108. Preparation of colloids. — There are a number of methods that may be used in the preparation of artificial colloidal solutions, but the description of only one will suffice in the present discussion. This is the use of a semipermeable membrane. It has already been mentioned that crystalloids pass with ease through a membrane such as parchment paper, while colloids do not. It is reasonable to expect, then, that these materials may be thus separated by proper adjustments. As a matter of fact, such a procedure is employed in many cases. The operation is called dialysis, and the membrane, itself a colloid, is designated as the dialyzing membrane.

For example, if a solution of ferric chloride, to which some ammonium carbonate has been added is placed in a dialyzer with pure water on the outside, the hydrochloric acid and other impurities gradually pass through the membrane and a more or less pure colloidal solution of ferric hydrate is left behind. The objection to this method lies in its extreme slowness. Nevertheless, since the cells of plants present a semipermeable membrane, this method of preparation serves to explain many actions that go on between soil and plant during the processes of nutrition. In the soil the formation of colloidal material is entirely a natural exertion of chemical and biological forces under such conditions that the particles split off are in that state of division which has been designated as colloidal.

It may be inferred that the quantity of colloidal matter in an average soil is large, but as a matter of fact this is not the case. The proportion of the soil in a colloidal state at any one time is very small. It must be remembered, however, that material is continually being thrown out of the colloidal condition and at the same time more

is generated; thus the effects may be marked, although the amount present at any one time is extremely minute.

100. **Colloids and soil properties.** — As may naturally be inferred, the influence of the colloidal matter on soil conditions, especially as related to plants, is extremely important. This influence is exerted in two ways. First, on cohesion and plasticity; and, secondly, on the adsorptive power of the soil. Both these qualities must be considered, not only in the physical, but also in the chemical and the biological, study of the soil as a medium for crop production.

In general it is found that, other conditions being equal, an increase of colloidal matter increases plasticity; in other words, the ease with which a soil may be worked into a puddled condition becomes greater. This is a rather undesirable quality when too pronounced, and in clays in which it is most likely to be developed some means of decreasing the colloidal influence is advisable. This great plasticity is developed because the colloids, especially those of a gelatinous or viscous nature, facilitate the ease with which the particles may move over one another and yet cohere sufficiently to prevent disruption of the mass. In general, also, the greater the plasticity of a soil, the greater is the cohesion when dry. In soils, then, in which the colloidal material is very high, clodding may occur if the soil is tilled too dry because of the great tendency of the particles to cohere. This cohesion and plasticity, as factors in soil structure, soil granulation, and tilth, will be discussed in the succeeding chapter. It is sufficient at this point only to observe the relationship of colloidal materials to the development of such qualities.

The second important attribute imparted to soil by

colloid development is high adsorptive power. This power extends not only to condensation of gases, but also to water and to materials in solution. The water of condensation on dry soil particles when exposed to a saturated atmosphere is largely determined by the colloidal content. In other words, the surface exposure of colloidal matter is so preponderant in water condensation as in a general way to allow the one to be a relative measure of the other. Again, colloids exert adsorptive power for material existing in the soil water, and to a limited extent compete with the plant for food. Until the colloids are satisfied the soil solution may not reach its maximum concentration for crop growth. This adsorptive power is exerted especially on the basic materials, such as calcium, and unless the existing colloids are fully satisfied the soil tends to become lacking in available bases. This condition is generally termed soil acidity. It may readily be seen that the concentration of the soil solution is governed to a considerable extent by the colloidal content of the soil, and that the adjustments in concentration are always toward an equilibrium between the two. Colloidal matter does not exert the same adsorptive power for all materials, but is capable of what might be called selective adsorption. For example, if ammonium sulfate is added to a soil, the ammonia is strongly taken up, which tends to release the sulfate. The continuous use of such a fertilizer on a soil poor in lime will ultimately result in the presence of free sulfuric acid. This example is sufficient to emphasize the relationship of adsorptive powers to fertilizer practice.

110. **Factors affecting colloids.** — It must not be inferred from the preceding discussion that the generation of colloids is detrimental to soil conditions. In light

soils the presence of such material is extremely necessary, as it tends to bind the soil together, facilitates granulation, and prevents loss of plant food by leaching. It is only in heavy soils in which such material is excessive that a detrimental condition is likely to exist. This occurs because of a high cohesion and plasticity, because of the competition for food that is likely to arise with the crop, and because of the tendencies toward acidity. Where lime is low or lacking, the situation has a tendency to become still more aggravated by further colloidal development.

In general, the practice of underdrainage by allowing the wetting and drying of the soil to proceed is the first step not only for the curbing of excessive and improper colloidal influence, but also for the encouragement of just the right development thereof. The freezing of winter, tillage at proper times, the addition of humus, and the application of lime are all practices that aid in the control of colloidal conditions. Since this control and utilization of colloidal influences is only a phase of soil structure as related to tilth and granulation, a further discussion of the subject will be reserved for later consideration.

111. Estimation of colloidal content. The colloids in the soil are so complex, so numerous, so variable in function, and so susceptible to change, that an exact determination of their amount is impossible. The knowledge of colloidal material in general is so meager that it is not surprising that such slight advances have been made in fully and clearly determining their character in a complicated material, as the soil undoubtedly is. The important methods of estimating the colloid content of the soil depend for their expression on the intensity of

certain qualities, supposed to be developed largely by colloid content. This indicates that the methods are largely comparative, rather than exact or strictly analytical in nature. These important methods[1] are three in number. Van Bemmelen's, Ashley's, and Mitscherlich's.

Van Bemmelen. — The first investigator to advance a method for colloid estimation was Van Bemmelen,[2] who considered that the amount of silica dissolved from a soil by digestion with hydrochloric or sulfuric acids was a measure of its colloidal content. It is now known that some materials, such as crushed rock, may yield as much silica with this treatment as a highly colloidal clay. This method is not of great importance at the present time, except as to the information that it gives regarding the evolution of colloidal soil study.

Ashley. — A second method, and one of much more value, has been evolved by Ashley.[3] He found that the adsorption of certain dyes by soils afforded a very good index to colloidal content. The difficulty in this method, however, lies in choosing the most effective dye and regulating its concentration. Moreover, different colloids vary so much in adsorptive capacity for the same dye, that only roughly comparative results have thus far been possible.

Mitscherlich. — The third, and as yet the most valu-

[1] A comparison of these methods is found as follows. Stremme, H., and Aarnio, B. Die Bestimmung des Gehaltes anorganischer Kolloide in zersetzten Gesteinen und deren tonigen Umlagerungsprodukten. Zeitsch. f. Prak. Geol., Band 19, Seite 329-349. 1911.

[2] Van Bemmelen, J. M. Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde. Landw. Ver. Stat., Band 35, Seite 69-136. 1888.

[3] Ashley, H. E. The Colloid Matter of Clay and Its Measurement. U. S. Geol. Sur., Bul. 388. 1909.

able, mode of colloidal estimation is that of Mitscherlich,[1] in which the adsorptive capacity of the soil is again made the comparative index. Water instead of dye is used as the adsorbed material. In this method the air-dry soil in a thin layer is brought to absolute dryness over phosphorus pentoxide. It is then placed in a desiccator over a 10 per cent solution of sulfuric acid and the condensation is hastened by a partial vacuum. The sulfuric acid is used in order to prevent the deposition of dew on the soil. After exposure for at least twenty-four hours the soils are found to have taken up their maximum moisture of condensation, which is called the hygroscopic water. The soil is then weighed, and the increase, figured to a percentage basis, is taken as a measure of colloidal content. The reverse process may also be followed, by exposing air-dry soil in a saturated atmosphere and afterwards drying over phosphorus pentoxide. The hygroscopicity of the soil, or its hygroscopic coefficient, is thus the basis for colloidal comparison. It is now clear why the term colloidal estimation is employed in this discussion, rather than colloidal determination.

An objection to the Mitscherlich method is advanced by Ehrenberg and Pick,[2] who claim that the drying over

[1] Rodewald, H., und Mitscherlich, A. E. Die Bestimmung der Hygroskopizität. Landw. Ver. Stat., Band 59, Seite 433-441. 1903. Also, Mitscherlich, E. A., und Floess, R. Ein Beitrage zur Bestimmung der Hygroskopizität und zur Bewertung der physikalischen Bodenanalyse. Internat. Mitt. f. Bodenkunde, Band I, Heft 5, Seite 463-480. 1912.

[2] Ehrenberg, P., und Pick, H. Beiträge zur physikalischen Bodenuntersuchung. Zeit. f. Forst- und Jagdwesen, Band 43, Seite 35-47. 1911. Also, Vageler, P. Die Rodewald-Mitscherlich'sche Theorie der Hygroskopizität vom Standpunkte der Colloidchemie und ihr Wert zur Beurteilung der Böden. Fühling's Landw. Zeit., Band 61, Heft 3, Seite 73-83. 1912.

phosphorus pentoxide will coagulate certain colloids and lower their adsorptive power, thus causing the hygroscopic coefficient to become an unreliable comparative figure. They suggest first the exposure of the field soil over the water and sulfuric acid, and then the extraction of the hygroscopic water over phosphorus pentoxide. Since this modification is very slow, the original Mitscherlich method, in spite of its faults, remains the most valuable up to the present time.

CHAPTER X

SOIL STRUCTURE

While texture is the term used in reference to the size of the particles in a soil mass, the word structure is employed in reference to the arrangement of the grains. The structural condition of the soil is very important to plant growth, since the circulation of air and water are so necessary to normal development. The structural condition may be loose or compact, hard or friable, granulated or non-granulated, as the case may be. Of these conditions, granulation, especially in heavy soils, is of vital importance, since it is really a summation of all favorable structural conditions. By granulation is meant the drawing together of the small particles around a suitable nucleus, so that a crumb structure is produced. The grains thus cease to function singly. The importance of such a structural condition on a heavy soil is very obvious. The soil becomes loose because of the larger units, air moves more freely, and water not only drains away readily when in excess, but responds with celerity to the capillary pull of the plant. Before the promotion of granulation and the factors that function therein may be clearly discussed, however, two properties of particular importance, especially in soils of fine texture, must be considered. These properties are plasticity and cohesion.

112. Plasticity. — Any material which allows a change of form without rupture, and which will retain this form

not only when the pressure is removed, but also when dry, is said to be plastic. Putty with a proper admixture of oil is a very good example of a plastic body. As is well known, the various plastic materials differ in their plasticity. Not only this, but such substances as clay or some other soils vary in plasticity with their moisture content, their granulation, and their texture. The great difficulty in the study of plasticity has been in finding a means of estimation allowing an exact numerical expression. The amount of hygroscopic water that a soil will hold has been used as an expression of plastic qualities, as well as shrinkage on drying, the ability to adsorb dyes, tenacity, and other characteristics. None of these has proved satisfactory, since one quality of a clay or other soil is used as a measure of another quality.

Atterberg[1] has suggested that the difference in moisture content of a clay at the point at which it ceases to be plastic, as compared with the moisture content at which it becomes viscous, might be used as an expression of plasticity. He has called this figure the plasticity coefficient. Thus, a soil may cease to be plastic at 30 per cent of moisture and may flow at 10 per cent. The plasticity coefficient would then be 20. While this is one of the latest methods, it is open to the objection already stated — that one quality of a soil is used as a measure of another. Two soils showing the same plasticity coefficient by this method may exhibit undoubted differences in actual plasticity. Kinnison,[2] in testing several methods of expression, found Atterberg's no better than others

[1] Atterberg, A. Die Plastizität der Tone. Internat. Mitt. f. Bodenkunde, Band 1, Heft 1, Seite 10-43. 1911.

[2] Kinnison, C. S. A Study of the Atterberg Plasticity Method. Trans. Amer. Cer. Soc., Vol. 16, pp. 472-484. 1914.

already in use. For all practical purposes in soil discussions, general descriptive terms may be employed.

113. **The cause of plasticity.** — Exactly what may be the cause of plasticity has long been under discussion. The various theories advanced may be grouped under the following heads:[1] —

A. Structure of clay particles
  1. Fineness of grains
  2. Plate structure
  3. Interlocking particles
  4. Sponge structure

B. Presence of hydrous aluminium silicates

C. Molecular attraction between particles

D. Presence of colloidal matter

Of these theories accounting for the plasticity of certain bodies, that of colloid content seems the most reasonable.[2] The presence of gelatinous colloidal matter, with a certain optimum amount of water, seems to facilitate the ready movement of the particles while at the same time exerting sufficient force to prevent the body from splitting apart at the time of movement, or when the pressure is removed or the material dried. Thus, in general, other conditions remaining equal, materials become more plastic the greater the content of colloidal matter. In general the colloids function as a measure of plasticity. The consideration of shrinkage, hygro-

[1] Davis, N. B., The Plasticity of Clay. Trans. Amer. Cer. Soc., Vol. 16, pp. 65–79. 1914.

[2] Cushman, A. S. The Colloid Theory of Plasticity. Trans. Amer. Cer. Soc., Vol. 6, pp. 65–78. 1904. Also, Ashley, H. E. The Colloid Matter of Clay and Its Measurement. U. S. Geol. Survey, Bul. 388. 1909.

scopic water, and dye adsorption as an expression of plasticity become logical on this basis.

114. **The importance of plasticity.** — Plasticity assumes considerable importance in a soil when it becomes highly developed, since it promotes ease in puddling. The more plastic a soil is, the more likely it is to become puddled by tillage, especially if it has a high moisture content. Thus a clay cannot be plowed wet, since this would allow its particles to be worked into that very intricate condition so detrimental to plant growth. A sand, on the contrary, may be stirred even when saturated, and still its structural condition will not be impaired since its plasticity is low or nihil. A very plastic soil is also likely to become exceedingly hard when dry unless it is well granulated, which shows the great care demanded by soils having high plasticity coefficients.

The three factors that affect plasticity to the greatest extent are texture, granulation, and moisture. In general, the finer the texture of the soil, the higher is the maximum plasticity thereof. The more granular a soil, the lower is the plasticity or the tendency to puddle when plowed. The amount of water is the third vital factor. A soil will exhibit its maximum plasticity at a definite moisture content. This point will be somewhere between the flowing, or viscous, condition and the point at which a soil refuses to mold, or, in other words, to become crumbly. With a soil such as a clay, in which the plasticity is high, plowing should be done when the moisture condition is such that there is no likelihood of puddling, and yet the soil will turn over with a maximum granulating effect.

115. **Cohesion.** — Very closely correlated with plasticity, but not in exact similarity, is cohesion. By the

cohesion of a soil is meant the tendency that its particles exhibit in sticking together and in conserving the mass intact. In general, the greater the plasticity of a soil, the higher is its cohesion, especially when it is dry or only slightly moist. For that reason, cohesion might be made a rough measure of plasticity. Cohesion of a soil occurs under two general conditions, the wet and the dry. When a soil is moist its cohesion is developed by the moisture films and the colloidal materials that may be present. This form of cohesion is often spoken of as *tenacity*. When a soil is dry its cohesion is developed to some extent by the interlocking of its grains and the deposition of cementing salts. The *greatest* force is developed, however, by the drying and shrinking of the gelatinous colloidal matter. As a general rule, the greater the amount of colloidal material, the more firmly the soil is bound together when dry, or, in other words, the greater is its cohesion.

Cohesion is important in tillage operations, in that soils having a high coefficient of cohesion tend to become cloddy when plowed and may thus be rendered poor in physical condition. This may be avoided by timing the operation so that the moisture content is somewhere above the point at which excessive cohesion is exerted. As cohesion is not greatly developed, except in a heavy soil, it is only where fine texture is found that such a danger exists. As already shown, the danger is a double one, for, since high plasticity and high cohesion go together, a soil plowed too wet may puddle while one plowed too dry may clod.

116. Methods of determining cohesion.— A number of methods have been devised for determining the cohesion of clays and other soils. One of the earliest was

Schübler's,[1] in which was tested the resistance of rectangular prisms of dry soils to penetration by a steel blade. The apparatus consisted of a beam supported on a fulcrum more than one third of the distance from the end. A pan for holding the weights added for causing the crushing was hung at the end of the long arm, while a counterpoise on the short end of the beam acted as a balance. The steel knife was placed on the long end of the arm near the fulcrum. The dry soil prism was placed under the knife and weights were added to the pan until crushing occurred. The weight necessary was designated as the cohesion coefficient of that soil.

Haberlandt[2] measured cohesion by crushing soil cylinders of a definite size. A glass vessel was placed on the top of the column and water was added until the column gave way. The weight necessary to bring this about was designated as the absolute cohesion of the sample. Haberlandt also measured cohesion of soil cylinders of a definite size by determining the resistance to breaking under a transverse load, the soil column being placed across supports six centimeters apart. On the column midway between the ends a scale pan was supported, into which weights were put until breaking occurred. The figure thus obtained was called the relative cohesion.

[1] A good description of Schübler's apparatus is found on page 104 of Bodenkunde, by E. A. Mitscherlich, published by Paul Parey, Berlin, in 1905.

[2] Haberlandt, F. Ueber die Kohärescenz Verhältnisse verschiedener Bodenarten. Forsch. a. d. Gebiete d. Agric-Physik., Band I, Seite 148-157. 1878. Also, Wissenschaftlich praktische Untersuchungen auf dem Gebiete des Pflanzenbaues, Band I, Seite 22. 1875.

Puchner[1] used a penetration apparatus, consisting of a vertical shaft held by metal guides and counterpoised by a weight hung over a pulley. The shaft was armed at the lower end with a cutting blade, while the upper end carried a scale pan for holding the necessary weights for penetration. The cohesion coefficient was the weight necessary to force the blade a certain distance into the soil. All important apparatus have been modeled after either Puchner's or Schübler's. That of Atterberg[2] (see Fig. 24) follows the former, while that of the Bureau of Soils[3] (see Fig. 25) resembles the latter.

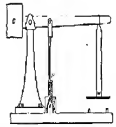

FIG. 24. — Atterberg's apparatus for determining the cohesion of soil prisms. The soil prism is placed between the cutting edge (K) and the sharp plunger (P). Weights are added at (W). (C) is a counterpoise.

[1] Puchner, H. Untersuchungen über die Kohärenz der Bodenarten. Forsch. a. d. Gebiete d. Agr.-Physik., Band 12, Seite 185–241. 1889.

[2] Atterberg, A. Die Konsistenz und die Bindigkeit der Boden. Internat. Mitt. f. Bodenkunde, Band II, Heft 2–3, Seite 149–188. 1912.

[3] Cameron, F. K., and Gallagher, F. E. Moisture Content and Physical Condition of Soils. U. S. D. A., Bureau of Soils, Bul. 50. 1908.

Recently Puchner[1] has found a machine for measuring the crushing strength of dry soil cylinders to be of value in determining the absolute, or maximum, cohesion of soils. The results, as he has already demonstrated in his previous work, are comparable, in relative value at least, to those obtained by simpler methods.

The great difficulty encountered in measuring the natural cohesion of a soil, either wet or dry, is not so

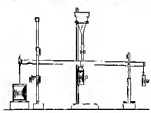

FIG. 35. — The apparatus used by the United States Bureau of Soils for determining the penetration of soils. (C) is mechanically packed soil; (A), steel point; (P), pail for receiving sand from funnel (F); (W) is a counterpoise.

much in the accuracy of the determination as in controlling physical conditions. The cohesion of a soil depends very much on the handling it has received in the preparation, in the amount of water that is added, and in the amount and length of time of drying. Natural granulation cannot be secured. The Bureau of Soils attempted to obviate these difficulties by mechanical sifting and packing, but the results were abnormal, due to the sifting process. As a consequence, most cohesion results

[1] Puchner, H. Vergleichende Untersuchungen über die Kohärenz verschiedener Bodenarten. Internat. Mitt. für Bodenkunde, Band III, Heft 2-3, Seite 141-230. 1913.

have been determined either on samples that have been worked to a maximum plasticity and then brought to the required moisture content, or on uniformly compacted samples that have been allowed to take up water by capillarity. In general the curve that would occur with normal granulation, while lower, will follow the direction of a maximum plasticity curve.

117. Factors affecting cohesion. — It is obvious, from what has already been said regarding the general characteristics of soils, that *texture* must play an important rôle in the determination of the cohesion factor. In general, the finer the texture, the greater is the cohesion, since, whether the soil is wet or dry, the forces that tend to hold the particles together are stronger than in a coarser soil. The drier the soil, however, the greater is the textural influence in this regard, due to the very great increase in the binding capacity of the colloidal matter on drying. In a coarse soil this binding effect is small or entirely absent.

Another factor is the *granular* condition of the samples. In general *granulation* may be said to be due to an exertion of cohesion between a limited number of particles, resulting in a crumb, or granular, structure. This granulation, by loosening the soil mass, lowers not only plasticity but cohesion also. The addition of organic matter to a soil, by loosening and increasing granulation, will tend to lower cohesion at every moisture content ranging from a dry to a saturated condition. The following data, taken from Puchner,[1] bring out the points just discussed:—

[1] Puchner, H. Untersuchungen über die Kohärenz der Bodenarten. Forsch. a. d. Gebiete d. Agri.-Physik., Band 12, Seite 195–241. 1889.

EFFECTS OF TEXTURE, GRANULATION, HUMUS, AND MOISTURE ON COHESION OF SOILS. (PUCHNER.)

Soil	Penetration in Grams at Various Moisture Contents					
	100 per cent	80 per cent	60 per cent	40 per cent	20 per cent	0 per cent
Clay	114	2,404	9,587	11,820	16,082	20,087
2 clay + 1 quartz .	30	437	6,304	13,370	13,204	15,704
1 clay + 2 quartz .	85	1,887	3,803	10,003	12,703	6,087
Quartz	187	2,987	4,237	5,137	8,370	2,770
2 clay + 1 humus .	44	764	4,704	7,404	9,587	12,087
1 clay + 2 humus .	59	1,010	1,704	4,204	5,070	1,687
Humus	115	1,414	1,904	1,804	870	487
Pulverized loam .	35	272	775	1,408	8,125	12,338
Granulated loam (granules .5-4 mm. diam.)	58	85	115	432	808	1,343

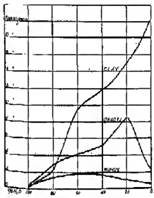

FIG. 38. — The effects of texture, humus, and moisture on the cohesion of soils.

The relationships already spoken of are especially well shown by the curves (see Fig. 28), particularly the effect of the moisture content on cohesion. In a heavy soil the cohesion increases steadily from a saturated condition until dryness is reached, the increase becoming accelerated as the percentage of moisture decreases. This is because

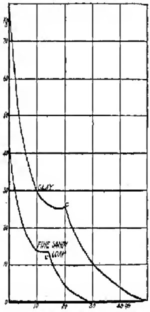

Fig. 27. — The cohesion curves of clay and fine sandy loam at various moisture contents. (C), point at which soil changes in color

the binding power of the colloidal material is greatly augmented by desiccation. In a coarse soil such as quartz, in which there is very little colloidal matter, the cohesion is developed principally by the water film. As this thins, its pulling power increases and the curve ascends; but when the soil dries this film disrupts and the curve drops again, having no colloidal binding material. The same relationships are shown by curves (see Fig. 27) adopted from recent determinations by Atterberg.[1]

118. Moisture limits for successful tillage. — In heavy soils, in which the colloidal content is usually high, plasticity and cohesion also are high. This means that the soil when too moist will be puddled by tillage implements, especially such as the plow, and when too dry clodding will occur because of very high cohesion. A moisture limit must therefore exist on a heavy soil, within which successful plowing may be done and maximum granulation results may be secured. That this moisture limit is narrow is obvious, since high cohesion and high plasticity bound it so closely on either hand. Such a relationship must be kept in mind not only by the farmer but by the technical man as well, since so much depends in any work upon good soil tilth. The relationship is clearly shown by the following curves (Fig. 28) partially adopted from Atterberg.[1] The cohesion and plasticity curves are seen to cross near the center of the diagram and indicate the existence of a zone where neither is exceedingly high or low.

In a clay soil a study of the optimum moisture condi-

[1] Atterberg, A. Die Konsistenz Kurven der Mineralböden. Internat. Mitt. f. Bodenkunde, Band IV, Heft 4-5, Seite 418-451. 1914.

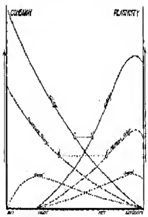

FIG. 38. — Diagram showing the moisture limits for successful plowing in soils of different class. aa' and bb' represent the moisture limits within which successful plowing may be accomplished on a clay and loam clay respectively.

tions is necessary in order to determine what is just the right moisture content for good plowing. That this condition must be carefully gauged and immediate use made of the advantages it offers is shown by its narrow limit. A few days may suffice for the moisture to drop through such a narrow area of fluctuation. A clay soil is so difficult to handle at best that no opportunities such as are offered by optimum moisture conditions should be lost. Moreover, a heavy soil plowed too dry or too wet does not regain its normal granular condition for several seasons.

In a sandy soil no such difficulties are encountered.

Since the soil has low cohesion, plowing when it is too dry will not clod, while, because of low plasticity, little puddling will occur if tillage is in progress when the soil is wet. Being always rather loose, such a soil is often benefited by plowing when it is slightly wet, the particles being brought into closer contact and excessive percolation being stopped while at the same time the water capacity is raised.

119. **Control of cohesion and plasticity.** — It is evident not only that cohesion and plasticity control the successful tillage of the land, especially where the soil texture is fine, but also that these same factors vary with the moisture and the granular structure of the soil. It has been shown that there is a moisture zone in all soils — this being narrower the finer the soil texture — at which neither cohesion nor plasticity is excessive. In this zone a heavy soil may be successfully plowed, with results favorable to the structural condition of the soil. Since the processes of granulation have already been shown to lower cohesion and plasticity, it is evident that as a crumb structure is developed the moisture zone for proper plowing will be widened, especially in a heavy soil. This is a very important point in the handling of clays and clay loams, since it not only opens a way for the elimination of the dangers of bad structural relationships, but also provides for putting the soil in a condition for easier and more convenient tillage. In a sandy soil, particularly where humus is the granulating agent, a soil with more cohesion, more plasticity, and a greater water-holding power is developed, all of which tend toward a better medium for plant growth. Methods of developing this granulation thus become the logical topic for further discussion.

120. Soil tilth.—The previous data and discussion have clearly shown the very great importance of a crumb structure in the working of the soil in the field. Since good physical condition will reflect itself on crop yield, it is evident that structure must ultimately be considered in relation to all plant growth. This relationship is usually expressed by the term *tilth*. While structure refers to the arrangement of the particles in general, and granulation to a particular aggregate condition, tilth goes one step further and includes the plant. Tilth, then, refers to the physical condition of the soil as related to crop growth. It may be poor, medium, good, or excellent, according to circumstances. Good tilth may demand in some soils maximum granulation, in others only a medium development. Maximum tilth always implies the presence of water, since the best physical relationships cannot be developed without optimum moisture conditions.

From the curves already presented, it is evident that an optimum moisture condition exists for the proper tillage of a soil, especially one of a heavy character. Also, an optimum moisture condition must exist for proper tilth, and therefore for proper plant development, since adequate tilth is the best physical condition for crop growth. Practical experience and theoretical evidence[1] have shown that these two optimum conditions are identical in nearly all cases, a happy coincidence in the practical management of a soil. The optimum moisture condition for plant growth, then, is the proper moisture condition for effective plowing. The optimum condition

[1] Cameron, F. K., and Gallagher, F. E. Moisture Content and Physical Condition of Soils. U. S. D. A., Bur. Soils, Bul. 50, p. 6. 1908.

for developing a favorable crumb structure is obviously the optimum moisture content for the development of the highest tilth. In fact, it can be stated with certainty that the optimum moisture condition for plant growth is the optimum for all favorable soil activities, whether physical, chemical, or biological. Granulation, then, becomes the vital factor in placing the soil in a physical condition such that the highest tilth, that physical criterion which every farmer should strive for, may be developed in any soil. Until proper granulation is reached, no soil can be expected to yield maximum paying returns.

121. **Granulation.** — While it is possible to list the factors that bring about granulation in a soil, it is difficult to state specifically just why this phenomenon takes place. It has been suggested that much of the granule formation in the soil is due to the contraction of the moisture film around the particles when, for any reason, the moisture content is reduced (see Fig. 29). It is known

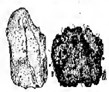

FIG. 30. — A puddled and a well-granulated soil.

that the soil particles tend to be drawn together by this reduction in the soil moisture, due to the pulling power of the thinned film. If to this condition is added a material which tends to exert not only a drawing power on loss of moisture, but also a binding and cementing power when dry, all

the essentials for successful granulation are present. This second force is found in the colloidal material present in considerable quantities in heavy soils. These are the same forces that have already been shown to determine the cohesion and plasticity of the soil, except that in granulating operations they are localized at numberless foci, and clodding or puddling is thereby prevented. It is evident that if cohesion and plasticity forces are to function for granulation — or, in other words, locally in the soil instead of generally and uniformly as when clodding or puddling occurs — a certain moisture content must be maintained. From what has already been shown, it is hardly necessary to restate that this moisture condition is near the optimum moisture content for plant growth.

Warington[1] attributes granulation to unequal expansion and contraction of the soil mass, due to the imbibition and loss of water. In a soil subject to such a condition, the cohesive forces being localized, the internal strains and pressures are unequal and a tendency arises for the mass to divide along lines of weakness into groups of particles. The binding capacity of colloidal material, as well as of salts deposited from the soil solution, tends to make such a crumb structure more or less permanent. Tillage operations, development of roots, burrowing of animals and insects, the presence of humus, and the formation of frost crystals, may assist in further developing these lines of weakness in the soil mass, on which the tension of the moisture films around the soil particles is brought to bear. The flocculation of soil particles may also develop lines of cleavage by their aggregation around

[1] Warington, R. Physical Properties of Soils, pp. 36 ff. Oxford. 1900.

certain centers. This movement of the soil particles is in every case facilitated by the presence of a moderate amount of moisture.

121. Forces facilitating granulation. — Granulation is nothing more or less than a condition brought about by the force exerted by a variable water film and the pulling and binding capacities of colloidal material, operating at numberless localized foci. It is evident that any influence or change in the soil which will cause a greater localization of these operative forces will promote increased granulation. The addition of materials from extraneous sources is also a practice that may tend to develop lines of weakness and thus cause a more intense localization of the forces at work.

The conditions, additions, and practices tending to develop or facilitate a granular structure in soils may be listed under six heads: (1) wetting and drying of the soil, (2) freezing and thawing, (3) addition of organic matter, (4) action of plant roots and animals, (5) addition of lime, and (6) tillage.

122. Wetting and drying. The drying of a soil has been shown to result in a drawing together of the particles into aggregates. When this process is repeated again and again by alternate wetting and drying, the influence on granulation becomes marked.

In drying, the small particles are moved into the spaces between the larger ones, thereby reducing the volume as is shown by the checks produced. These checks that result from shrinkage are due to the unequal contraction. There comes a time when the general film around the whole mass must rupture, and it breaks along the lines of least resistance. If the soil mass is very uniform, there will be few breaks and the shrinkage will be mainly around

a relatively few centers. This process produces clods, or "overgrown" granules. If there are numerous lines of weakness, however, there will be many centers of contraction, and consequently a larger number of small clods, or granules, will be formed. This is the desirable condition and constitutes good tilth — that is, the most favorable physical condition for plant growth.

Just what may be the effects of wetting and drying on the colloidal matter of soil is a question. In general, desiccation tends to flocculate colloids and in many cases their binding power becomes highly developed thereby. If such colloids are irreversible, as many in the soil undoubtedly are, this binding becomes more or less permanent, which explains the tendency for a crumb structure to persist. Wetting, on the other hand, tends to develop colloidal matter which will become binding material on the next drying. The desiccation and throwing down of colloids, as well as their generation, thus becomes a very important factor in the wetting and drying as related to granulation.

The following figures[1] represent the relative force necessary to penetrate puddled clay dried once, as compared with the same puddled soil wet and dried twenty times. The relative hardness may be taken as a rough measure of granulation: —

	Percentage of penetration
1. Puddled clay dried once	100.0
2. Puddled clay dried twenty times .	31.4
3. Puddled clay dried twenty times .	30.8
4. Puddled clay dried twenty times .	32.0

[1] Fippin, E. O. Some Causes of Soil Granulation. Trans. Amer. Soc. Agron., Vol. 2, pp. 106-121. 1910.

The fact illustrated above has many practical applications. It should be observed that the change in structure is not associated with continual wetness, nor is it identified with a continued dry state. In neither condition is any force brought to bear on the particles. The force is exerted only during the drying process and the wetting process. It is a well-known fact that soils which are continually wet are usually in bad physical condition. In the drainage of wet land, it is found that the soil is at first very refractory, but when good drainage is established there is a gradual amelioration of the physical condition, which is primarily a change in structure. On the other hand, in a soil continually in a dry state there is no change in granulation. The improvement of soil structure, as a result of changes in the moisture content, is dependent largely on lines of weakness in the soil mass. Some of these are produced in the process of drying, and others in the ways already listed.

124. **Freezing and thawing.** — As will be seen in the consideration of soil moisture, the water is distributed in the fine pores of the soil. When it freezes it forms long, needle-like crystals. This crystallizing force is very great, amounting to about 150 tons when a cubic foot of water changes to ice. In freezing, the crystals gradually grow first in the larger spaces. During this process there is a marked withdrawal of moisture from the smallest spaces, so that the ice crystals in the large spaces may be built up. The soil mass is separated by the crystals, and as the result of even a single hard freeze a wet, puddled soil is shattered into pieces. The repetition of this process by subsequent freezing and thawing will further break up the soil by creating new lines of weakness. The granulating power of freezing and thawing is shown in the following

figures,[1] expressed as the relative force necessary to penetrate a puddled clay treated in various ways: —

	Percentage penetration
1. Puddled clay dried once	100.0
2. Puddled clay frozen once and dried once	30.3
3. Puddled clay frozen three times and dried once	22.3
4. Puddled clay frozen five times and dried once . .	21.8

Freezing probably affects the colloidal material in the same general way as does drying. This has been indicated by the work of certain investigators,[2] in which it was found that lowering the temperature of a soil below freezing lowered the hygroscopic coefficient.

125. Addition of organic matter. — Soils rich in humus or decomposed organic matter are generally in better physical condition than soils low in organic content. The marked effect of the absence of this material in many long-cultivated soils is well known. For example, in much of the southern New York hill regions, the soils are now recognized to have a very different relation to crop growth from what they had for a few years after they were cleared. Their color has become lighter, and with the decay of the humus a decided physical change has taken place in the soil, which is to some extent corrected by the restoration of the organic content. In certain prairie soils the effect of humus depletion on struc-

[1] Fippin, E. O. Some Causes of Soil Granulation. Trans. Amer. Soc. Agron., Vol. II, pp. 106-121. 1910.

[2] Czermak, W. Ein Beitrag zur Erkenntnis der Veränderungen der sog. physikalischen Bodeneigenschaften durch Frost, Hitze, und die Beigabe einiger Salze. Landw. Ver. Stat., Band 76, Heft 1-2, Seite 75-116. 1912. Also, Ehrenberg, P., und Romberg, G. F. von. Zur Frostwirkung auf den Erdboden. Jour. f. Landw., Band 61, Heft 1, Seite 73-86. 1913.

ture is even more marked. While the actions of humus are many, as has already been shown, its relationship to physical condition is always particularly emphasized.

Humus contains much colloidal material and in this way possesses a certain degree of plasticity. It is, however, of a very loose structure and the large spaces constitute lines of weakness. Another property of humus is that it undergoes great change in volume when dried out — a property akin to the fineness of the soil, producing larger shrinkage cracks. This is noticeable in many black clay soils, which check excessively. The great capacity of humus for moisture permits a wide range in moisture content, which produces corresponding physical alteration. This wide swing from one extreme to another is a potent factor in granulative influences. The color of the humus affects the color of the soil, and thereby increases the rate of change from the wet to the dry state by increased evaporation of moisture. The relative effects of crude muck, and the ammonia extract from the same muck, on the cohesion of a puddled clay, as indicated by the force required for a uniform penetration of a knife-edge, is shown in the following table; the samples were dried and rewetted twenty times:

PUDDLED CLAY PLUS MUCK[1]

	Percentage of penetration
1. Clay	100
2. Clay plus 5 per cent of muck	82
3. Clay plus 15 per cent of muck	73
4. Clay plus 25 per cent of muck	58
5. Clay plus 50 per cent of muck	50

[1] Fippin, E. O. Some Causes of Soil Granulation. Trans. Amer. Soc. Agron., Vol. 2, pp. 106-121. 1910.

Puddled Clay plus Muck Extract[1]

	Percentage of puddling
1. Clay	100
2. Clay plus 1 per cent of extract	65
3. Clay plus 2 per cent of extract	26
4. Clay plus 4 per cent of extract	18

126. **Action of plant roots and animals.** — The extension of plant roots changes the soil structure by forcing the particles apart at each growing root point, and possibly also by some action yet to be explained. Crops differ greatly in their effect on soil structure. Grass, millet, wheat, and other plants with fine roots are more beneficial to tilth than coarse or tap-rooted plants such as corn, oats, and beets. Grass affects structure also by protecting the surface of the ground. It is advisable to establish a rotation on clay soil, that plowing may be done at frequent intervals and that plants with different root developments may be given an opportunity to exert their influences. The organic matter left in the soil by decaying roots is always in very intimate contact with the soil grains and has much to do with accelerating granulation.

Animals also affect soil structure. Earthworms, by carrying materials to the surface, exert a mixing effect, while the lines of seepage and zones of weakness developed through their burrowing proclivities are of no mean importance. Insects, especially ants and other burrowing creatures, aid in this and in other ways.

[1] Fippin, E. O. Some Causes of Soil Granulation. Trans. Amer. Soc. Agron., Vol. 2, pp. 106-121. 1910.

127. **Addition of lime.** — One of the important effects of lime is in its flocculating action. This agglomeration, as already explained under colloids, is the drawing together of the finer particles of a soil mass into granules. When caustic lime is mixed with water containing fine particles in suspension, there is almost immediately a change in the arrangement of the particles. They appear first to draw together in light, fluffy groups, or floccules, which then rapidly settle to the bottom so that the supernatant liquid is left clear or nearly so. This phenomenon is termed flocculation, because of the groups of particles. It is not an action limited to caustic lime alone, however, but because of the usefulness of this compound in other ways, and because of its very strong action, it is ordinarily used on soils. This flocculating tendency when caustic lime is added goes on in the soil as well as with suspensions, although more slowly. In general the lime serves to satisfy the adsorptive capacity of the colloidal material, and by throwing down these colloids develops lines of weakness. The cohesive power of the soil is thus localized and granulation must necessarily occur.

The various forms of lime differ in their granulating capacities, calcium oxide and calcium hydrate being very active while calcium carbonate is relatively inactive in this regard. For this reason, if flocculation effects are desired, the oxide or hydrate combinations are added. The relative influences of lime on puddled clay as measured by penetration is shown in the following table;[1] the soil was dried once and the untreated soil was used as 100 per cent: —

[1] Fippin, E. O. Some Causes of Soil Granulation. Trans. Amer. Soc. Agron., Vol. 2, pp. 106–121. 1910.

	Percentage of penetration
1. Puddled clay	100
2. Clay plus 2 per cent CaO	56
3. Clay plus 4 per cent CaO	43
4. Clay plus 6 per cent CaO	33
5. Clay plus 5 per cent $CaCO_3$	98
6. Clay plus 10 per cent $CaCO_3$	111
7. Clay plus 25 per cent $CaCO_3$	95

In the soil the oxide and hydrate revert to the carbonate, but before this change occurs the flocculating effects have been exerted and the lines of weakness so essential to granulative processes have been developed. Lime really does not produce granulation in a normal soil through its own action alone, but is aided by the other influences already discussed.

Warington[1] reports a statement of an English farmer to the effect that by the use of large quantities of lime on heavy clay soil he was enabled to plow with two horses instead of three. It is generally true that soils rich in lime are well granulated, and maintain a much better physical condition than soils of the same texture that are poor in lime.

128. Tillage. — The effect of tillage on soil structure is to produce lines of cleavage, and these, when produced by plowing, are multitudinous and fairly uniformly distributed. Plowing, when the moisture content is suitable, tends to break the soil into thin layers, which move one over the other like the leaves of a book when the pages

[1] Warington, R. Physical Properties of Soil, p. 33. Oxford. 1900.

are bent. This disturbance of the existing arrangement of particles puts in motion the two forces that have already been discussed, the pull of the water film and the binding power of the colloidal matter. The strength of cohesion between small particles, such as clay, can be realized when one considers the tenacity with which these particles are held together in dried puddled soil. This cohesive attraction is inversely proportional to the square of the distance between the centers of the attracting bodies. Particles that can be brought as closely together as can clay particles may be thus held with great firmness. The effect of tillage when an excess of water is present is to force the particles into large masses and bring about a generalized exertion of the forces of plasticity. The soil then becomes puddled. Tillage when the soil is too dry results either in clodding or in the soil's becoming so pulverized that it becomes puddled on wetting. As already emphasized, proper pulverization by tillage, especially by plowing, may occur only when the soil is in optimum moisture condition.

129. **The action of the plow.** The plow brings about its effects because of the differential stresses set up in the furrow slice as it passes over the share and the moldboard. The soil in immediate contact with the plow surface is retarded by friction, and the layers above tend to slide over one another much as the leaves of a book when they are bent. If the soil is in just the right condition, maximum granulation results; but if the moisture is too high or too low, puddling or clodding may follow, especially on a heavy soil. Not only does a shearing occur, but this shearing is differential, due to the slope of the share and especially to the curve of the moldboard. Where the soil is to be turned over with the least expenditure of

force, the share is sloping and is set to deliver a slanting cut, and the moldboard is long and gently inclined. This allows the furrow slice to be turned with little granulation and a minimum expenditure of energy. When maximum granulation and pulverization are desired, the moldboard is short and sharply turned, and the share is less sloping and the cutting edge is less slanting. Such conditions make for the development of more friction and the generation of those internal twisting and shearing stresses necessary for good granulation. The sharper the bending of the furrow slice, the greater are the internal stresses set up. While the plow is the very best pulverizing agent when optimum soil moisture conditions prevail, it is also a most effective puddling agent when the soil is wet. Therefore care in the judging of optimum conditions for plowing is a most important feature in the maintenance and encouragement of soil granulation and tilth.

130. **Résumé.** — The factors controlling the structural condition of any soil are found to be plasticity and cohesion. As these increase, the tendencies of a soil to puddle when wet and to clod when dry are augmented. Therefore, in heavy soils a decrease in these factors is advisable, through a careful control of moisture and a bettering of the granular structure of the soil. Granulation, while due to some extent to the localized influence of the water film, is traceable largely to the colloidal matter which acts as a binding agent. It is really a concentration of the forces of cohesion and plasticity around numberless localized foci. Granulation takes place under the influence of wetting and drying, freezing, plants and animals, addition of humus and lime, and tillage operations, especially plowing. Due to the high cohesion and plasticity of heavy soils, the moisture zone

for successful plowing is relatively narrow. The ability to detect when this zone has been reached in a clay soil is one of the essentials of successful soil management. Another essential is the effective widening of such a zone by granulation operations. The optimum moisture condition for tillage is also the optimum condition for plant growth — a happy coincident, since by regulating the moisture content for plant development conditions are rendered most favorable for all soil activities. It is thus possible to realize that criterion in all soil physical operations, a maximum tilth.

CHAPTER XI

THE FORMS OF SOIL WATER AND THEIR MOVEMENT

Under all normal conditions the soil bears a certain amount of moisture, which must be reckoned with in any study whether of a practical or of a theoretical nature. Moreover, the amount of water varies in its characteristics according to its position. It also has movement, which goes far in determining its usefulness to plants. Before a discussion of the different forms of water, their movement, and their availability to plants, may be entered into, however, some way of quantitatively stating the amounts present must be determined upon.

131. Methods of expressing soil moisture. — During the many years of soil investigation, especially where the problems had to deal either directly or indirectly with moisture, five methods of water expression have been evolved, their use depending on the nature of the work and on the points to be expressed. These may be listed under two general heads: —

A. Percentage expression
   1. Percentage on a wet basis
   2. Percentage on a dry basis

B. Volume expression
   1. Cubic inches to the cubic foot of soil
   2. Percentage by volume
   3. Surface inches

The simplest way of explaining the application of these methods for the expression of the amount of water in a soil is by a specific case. Suppose a certain soil in field condition weighs 100 pounds to a cubic foot and carries 10 pounds of water. Obviously it would contain 10 per cent of water by the wet method of calculation, or 11.1 per cent of water, using the absolutely dry soil as a basis. A pound of water contains 27.6 cubic inches; therefore the amount of water carried by this soil expressed by volume would be 276 cubic inches for every cubic foot of soil. The percentage by volume would equal $(276 : 1728) \times 100$, or about 16 per cent. An inch of water covering the top of a cubic foot weighs 5.2 pounds. Obviously the number of surface inches which this 10 pounds of water would occupy if placed on the top of the cubic foot of soil would be $10 \div 5.2$ or 1.92 surface inches.

The first method of moisture expression, as percentage on a wet basis, is open to two serious objections. In the first place, two different percentages of water in different samples of the same soil do not represent the same degrees of wetness as are expressed by the percentages. For example, 100 grams of wet soil containing 5 per cent of water would consist of 5 grams of water and 95 grams of soil, a ratio of 1 to 19. If the soil contained instead 25 per cent of water, the ratio would be 1–3 instead of 1–3.8, as the ratio of the percentages would naturally lead one to expect. The second objection is just as serious and arises from the fact that soils have different apparent weights. For example, 5 per cent of water on the wet basis for a clay weighing when dry 70 pounds to the cubic foot would equal 3.68 pounds, while 5 per cent on a sand weighing 100 pounds would give 5.26 pounds of the same volume. The error of such a method of expression is

obvious, not only in comparing the water content of the same soil, but in comparing different soils as well.

In using a percentage of moisture based on the dry soil instead of on the wet, the first of the above objections is eliminated. Consequently this method of expression is perfectly legitimate as long as soils having about the same apparent specific gravity are compared. As soon as soils of different weights are considered, however, a more nearly accurate method must be employed. Obviously, then, the only really rational mode of moisture statement is by the volume method. In ordinary calculations of water, however, the percentage by dry weight is generally used because of its simplicity and the facility of expression that it affords. It is also much easier to establish than a percentage based on volume.

The first and second methods of volume expression are of about equal value as far as direct comparison goes. For the actual water present the number of cubic inches to a cubic foot of soil is perhaps preferable, as it shows the exact amount of water contained and may easily be converted to pounds to a cubic foot or tons to an acre as the case may be. The third volume statement is generally used in field practice, especially in irrigated regions, where water is measured in inches in depth to an acre of area. Such a statement of the available water in a soil not only is convenient, but also gives a direct comparison with the probable rainfall of the growing season.

132. Kinds of water in the soil. — As has already been demonstrated, a soil of a definite volume weight has a definite pore space which may be occupied by air or by water, or shared by both, as the case may be. Of course, an ideal soil for plant growth is one in which there is both air and water, the proportions depending on the

texture and the structure of the soil and the character of the crop. Assuming for the time being, however, that the pore space is entirely filled with water, or, in other words, that the soil is saturated, three forms of water are found to be present — hygroscopic, capillary, and free, or gravitational. These forms differ, not in their composition, but in the position that they occupy in relation to the soil particles.

The hygroscopic and capillary water are both film forms; that is, they surround the soil particle, being held partly by the attraction of the particle and partly by the molecular attraction of the liquid for itself. The hygroscopic film is very thin, being water of condensation, or adsorption. When this film is satisfied and moisture is still present, the capillary water film begins to form. The line of demarcation between hygroscopic and capillary water is not sharp. The general difference between the two forms may be considered as being not only one of position, but also one of movement, this power being possessed only by the capillary film. With a change in any controlling condition, such as temperature, hygroscopic water may change to capillary, or capillary water to hygroscopic, as the case may be. As the capillary water continues to increase and the film becomes thicker and thicker, a point is at last reached at which gravity overcomes the surface tension of the liquid and drops of water form which tend to move downward through the air spaces, being now subject to movement by the attraction of gravity. Free, or gravitational, water then also becomes present in the soil. If water is still added, the gravitational water continues to increase until the air is almost entirely displaced and a saturated condition results. There may be a change of capillary to free water

or of free water to capillary with a change of structure, temperature, or pressure, as was seen to be the case between the hygroscopic and capillary moisture. The forms of water present in a saturated soil may be conveniently represented by the following diagram:

HYGROSCOPIC | CAPILLARY | FREE

FIG. 30. — Diagram representing the three forms of water that may be present in a soil.

183. **Hygroscopic water.** — The hygroscopic water in a soil has been spoken of as the water of condensation, or adsorption. It is, however, quite distinct from water condensed on a surface colder than the atmosphere in which it is placed. All bodies possess the power, to a greater or less degree, of adsorbing water even when at the same temperature as the air with which they are in contact, provided, of course, that the air contains water vapor. The hygroscopic film may be continuous or only partly continuous, depending on the condition of the surface. In fact, the movement of water over surfaces is often greatly facilitated by an already existing hygroscopic film. External conditions being constant, the amount of hygroscopic water of various materials is determined by two factors: (1) the characteristics of the material itself, and (2) the amount of surface it exposes.

It is a well-known fact that various materials differ in the amount of hygroscopic water they will hold, due to the attraction of the substances themselves for water. The differences in the thickness of the film is so slightly altered, however, by differences in materials, that, other factors being constant, the hygroscopic water becomes a function almost entirely of surface. Glass becomes

far more hygroscopic when pulverized. Porous bodies are especially high in hygroscopic water, sometimes holding as much as 20 to 30 per cent of moisture. The following data, drawn from Ammon[1] and von Dobeneck,[2] although no doubt faulty, illustrate the differences in hygroscopicity of materials commonly found in soils and make plain the complexity of the question when applied to soil phases: —

Percentage of Hygroscopicity of Different Substances at 20° C. when Exposed for One Day to Saturated Air

	Ammon	Von Dobeneck
Humus	15.96	18.04
Ferric oxide	18.70	20.41
Kaolin	.47	3.35
Limestone	.20	.33
Quartz	.07	.17

One of the characteristics peculiar to colloids in particular is a high adsorptive power for moisture, this giving them properties not usually possessed by crystalloids. Gelatinous precipitates of silica, ferric oxide, and aluminium oxide are good examples. Colloidal humus, gelatin, and agar are noted for their adsorptive powers. The water in such cases is not simply adsorbed on the external

[1] Ammon, Georg. Untersuchungen über das Condensationsvermögen der Bodenconstituenten für Gase. Forsch. a. d. Gebiete d. Agri.-Physik, Band II, Seite 1–46. 1879.

[2] Dobeneck, A. F. von. Untersuchungen über das Absorptionsvermögen und die Hygroskopizität der Bodenkonstituenten. Forsch. a. d. Gebiete d. Agri.-Physik, Band XV, Seite 163–228. 1892.

expanses, but is distributed over the great internal surface exposure. Such water cannot be expelled by ordinary drying, but the material must be subjected to a high heat in order to drive off even a part of the water so held. The question is greatly complicated also by the fact that some bodies have a chemical affinity for water. This results in the formation of hydrates and other salts. Such water cannot be expelled without the breaking-up of the compounds.

Ordinary soil possesses to an extraordinary degree the three characteristics already cited: that is, it exposes a very large amount of free surface; it tends to generate continuously large amounts of colloidal material such as ferric hydrate, aluminium hydrate, silicic acid, and especially humic materials in a colloidal state; and it always has present compounds having an affinity for water. However, since these compounds are easily satisfied, and also since the adsorptive power of colloids is due to the surface exposed, it may be considered that, other conditions being equal, the hygroscopicity of the soil is essentially a surface phenomenon. Although for all practical purposes hygroscopicity may be considered as having special relation to surface, exact correlation is not easy partly because of the difficulty of accurately determining the surface exposed by a normal soil.

134. Effect of texture and humus on hygroscopicity. — The question being thus reduced to a surface consideration, it is evident that the texture of the soil, external factors being under control, is the determining factor. The following figures from Loughridge,[1] by whom the hygroscopic

[1] Loughridge, R. H. Investigations in Soil Physics. California Agri. Exp. Sta., Rept. of Work of the Agri. Exp. Stations of California for 1892-3-4, pp. 76-77.

moisture was determined by exposing the air-dry soil at 15° C. to a saturated atmosphere and then drying at 100° C., illustrate this point: —

HYGROSCOPIC CAPACITY OF VARIOUS SOILS

SOILS	PER CENT CLAY MATERIAL REMAINING IN SUSPENSION AFTER STANDING FOR 24 HOURS	HYGROSCOPIC WATER EXPRESSED IN PERCENTAGES
15 clays	31.07	10.45
7 clay loams	17.15	6.06
9 loams	12.06	5.18
6 sandy loams	7.30	2.50
4 sands	3.93	2.30

Apparently, the finer the soil, the greater is the hygroscopicity. The finer the soil, the higher also is the percentage of clay, and consequently the greater is the amount of material likely to be present in a colloidal state. As a matter of fact, the hygroscopic moisture as shown above is roughly proportional to the clay; and as clay, especially the finer forms, is largely colloidal in nature, the colloidal content of a soil practically determines the hygroscopic content. This fact is the basis for Mitscherlich's[1] method of colloid estimation, in which hygroscopic moisture determined under certain controlled conditions is used as a relative measure of colloidal content. The various grades of particles constituting the textural make-up of a soil, then, do not possess the same weight in the determination of hygroscopicity, the dominant grade being clay, especially that part which has, by either physical

[1] Mitscherlich, E. A. This text, paragraph 111.

or chemical means or both, been thrown into a colloidal condition. Especially do the humous colloids, as has already been shown, function in this regard, so that the organic matter must be of very great importance in determining the hygroscopic capacity of any soil. The finer the soil, the greater is the amount of hygroscopic water merely because of the large area of surface exposed. Also, any practice that will increase the colloidal material — the humous colloids being very susceptible to increase by proper soil management — the higher will be the percentage of this hygroscopic moisture. Texture and humus, then, govern the hygroscopicity of most soils.

186. Nature of the film. — The nature of this thin film which is designated as hygroscopic water has not as yet been determined. Held so strongly by a molecular force averaging probably 10,000 atmospheres, generated by adhesion and cohesion, it is not definitely known whether the film exists as a liquid or a vapor. Consequently it cannot be expected to conform to the laws that are generally found to apply to capillary films. In many cases the film may not be continuous, and being so very, very thin, it may even possess a negative surface tension. The radius of influence of a particle in water has been shown by Chamberlain[1] to be about 1.5×10^{-7} centimeters. Within this zone the molecules of water are much restricted in their motions. The thickness of the hygroscopic film on quartz particles as calculated by Briggs[2] is 2.00×10^{-8} centimeters, showing that the outer edge of the hygroscopic

[1] Chamberlain, C. W. The Radius of Molecular Attraction. Physical Review, Vol. 31, pp. 170-182. 1910.

[2] Briggs, L. J. On the Adsorption of Water Vapor and of Certain Salts in Aqueous Solution by Quartz. Jour. Phys. Chem., Vol. 9, pp. 617-641. 1905.

film, where the water to a large extent loses its movement, is considerably without this zone of influence. In order to give some idea of the extreme minuteness of the hygroscopic film, it may be said that its thickness is less than the diameter of the smallest known soil bacteria. In moving from the surface of a particle outward through an ordinary water film, passage is first made through the zone of influence. When the edge of this is reached, an area is passed through which continues with constantly increasing capacity for molecular motion until the outer edge of the hygroscopic film is crossed, where molecular activity reaches its maximum.

136. Effect of humidity and temperature on hygroscopic water. — Two external conditions seem to affect the amounts of hygroscopic water that a soil may hold under definite conditions — humidity and temperature. As a general rule, the higher the humidity, the higher is the hygroscopic moisture. The experiments of von Dobeneck[1] with quartz and humus illustrate this point: —

PERCENTAGE OF HYGROSCOPIC WATER HELD AT VARIOUS HUMIDITIES AFTER AN EXPOSURE OF TWENTY-FOUR HOURS AT 20° C.

	30 Per cent	50 Per cent	70 Per cent	90 Per cent	100 Per cent
Quartz . . .	.045	.053	.078	.119	.175
Humus . . .	4.054	7.766	10.589	15.670	18.014

The results as to the effects of a rise in temperature on the hygroscopic film are not so definite. Most in-

[1] Dobeneck, A. F. von. Untersuchungen über das Absorptionsvermögen und die Hygroskopizität der Bodenkonstituenten. Forsch. a. d. Gebiete d. Agri.-Physik, Band XV, Seite 163-228. 1892.

vestigators[1] find that as the temperature is increased the hygroscopicity becomes lowered, thus following the general laws of adsorption. Hilgard, however, obtained opposite results when the air was saturated, although his data agreed with previous results when hygroscopicity was studied in an atmosphere unsatisfied as to its capacity for water vapor. King[2] explains this discrepancy as being due to the very high vapor pressure generated by a saturated atmosphere at high temperatures, causing a more rapid taking-up of water by the soil than was lost from its surface. The time necessary for a soil to assume its maximum thickness of adsorbed water is uncertain. Hilgard[3] used seven hours in his determinations, while Mitscherlich[4] exposed his soil for several days. A soil continues to increase in weight slowly as its time of exposure to moist air is increased, so that a sharp line of demarcation between capillary and hygroscopic water is difficult to establish. Capillary water may even be present in the minute interstices before the hygroscopic film is elsewhere satisfied.[5]

137. **Determination of hygroscopicity.** — The method of the determination of the maximum hygroscopicity of a soil, or, in other words, the hygroscopic coefficient, is simple in outline. The soil, in a thin layer, is exposed

[1] Patten, H. E., and Gallagher, F. E. Adsorption of Vapors and Gases by Soils. U. S. D. A., Bur. Soils, Bul. 51, p. 33. 1908.

[2] King, F. H. Physics of Agriculture, pp. 179-180. Published by the author, Madison, Wisconsin, 1910.

[3] Hilgard, E. W. Soils, pp. 196-201. New York. 1911.

[4] Mitscherlich, E. A. Bodenkunde, pp. 56-58. Paul Parey, Berlin. 1905.

[5] Briggs, L. J. The Mechanics of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 10, p. 12. 1897.

to an atmosphere of definite humidity under conditions of constant temperature and pressure. Complications arise from the necessity of using a very thin layer of soil, from the difficulty of controlling humidity, and from the tendency of capillary water to form in the soil interstices before the hygroscopic film is satisfied. The question of how long the exposure should take place is a very serious factor, as has already been pointed out. In the drying of the soil after exposure a vexing condition also is encountered, in that as the temperature is raised, the giving-off of water vapor continues. It is evident, therefore, that not only must any method be more or less arbitrary, but that its value can be only comparative. The method of Mitscherlich, as already described,[1] is probably the most nearly accurate. He exposes the dry soil under partial vacuum over 10 per cent sulfuric acid and water. The partial vacuum is to hasten adsorption, and the acid to prevent a fully saturated air, thereby cutting down chances of dew deposition.

138. Heat of condensation. The amount of energy necessary to expel the hygroscopic film from around a soil particle is very great, since its only movement is thermal. As a matter of fact, it is really impossible to divest the soil grain entirely without causing the loss of moisture other than that simply adsorbed. As so much energy is expended in removing this film, it is reasonable to expect that a certain amount of heat of condensation when the film is resumed would become apparent. Patten[2] offers the following quantitative data concerning this point: —

[1] Mitscherlich, A. E. This text, paragraph 111.

[2] Patten, H. E. Heat Transference in Soils. U. S. D. A., Bur. Soils, Bul. 59, p. 34. 1909.

P

HEAT EVOLVED IN WETTING SOILS DRIED AT 110° C.

Soil	Calories per Kilo of Dry Soil
Coarse quartz	150
Podunk fine sandy loam	200
Norfolk sand	347
Hagerstown loam	1108
Galveston clay	3785
Muck soil (25 per cent organic matter)	6413

139. Capillary water. — It has been shown in the previous discussion that a large proportion of the hygroscopic film is beyond the radius of influence of the particle and is not held so rigidly as is the inner portion. In other words, in this film a certain amount of molecular movement is possible, this movement depending on the distance from the particle. As soon, however, as the boundary of the hygroscopic film is crossed, a comparatively thick film of moisture is reached in which molecular movement, except for the influence of viscosity, is perfectly free and unimpeded. These two zones (see Fig. 31) — one in which capillary movement is more or less free, and a comparatively thin film in which molecular movement becomes increasingly sluggish as the radius of influence of the soil grain is approached, — are therefore clearly differentiated. The capillary water differs from the hygroscopic moisture (1) in that it is largely in a liquid state and consequently is governed by the ordinary laws of liquids; (2) in that it evaporates at ordinary

FIG. 31. — Diagram showing the relationship of the hygroscopic and capillary water films surrounding a soil particle. (a), particle; (b), zone of influence of particle; (c), outer edge of hygroscopic zone; (d), capillary film.

temperatures, being held with less tenacity; and (3) in that it has the power of movement from place to place within the film, hence the name capillary water.

140. Surface tension and the force developed thereby. — The power that tends to hold this capillary water in place against the force of gravity, a constant, depends on the surface tension of the liquid. This phenomenon of surface tension is due to the existence of certain molecular forces acting from within. In a drop of water, for example, the particles are attracted equally in all directions and consequently are able to move with perfect freedom. The molecules on the surface of the drop, however, are not in such an equilibrium of attraction, since the pull of the water particles within is greater than that of the air particles without. The resultant attraction is therefore inward, and is directed along a line perpendicular to the surface at that point. The result is the development of a more or less ideal membrane, the effective force of which is not affected by the amount of the surface, but by the curvature. In a sphere the force or pressure developed by surface tension is equal to twice the surface tension divided by the radius. This increase of the effective force by curvature of film is very important as regards soil water, since, as will be shown later, it governs the movement of capillary water from one particle to another, the direction of the movement being determined by a difference in pressure as developed by unequal curvatures of film surfaces.

As a result of this force developed by surface tension, the water film around a soil particle tends to equalize itself until this pressure is everywhere the same. On this force depends also the thickness of the capillary film. Under any given condition this capillary film will con-

tinue to thicken until the mass of the water is so great as to allow gravity to come into play and pull enough water away to again restore the equilibrium. The soil particle would at this point be maintaining its maximum thickness of capillary film. It is also quite evident that as the capillary film is thinned — as, for example, by evaporation — the force developed by surface tension would be increased, due to increased curvature of the film, and the difficulty of removing the external layers of the film would naturally become greater.

141. **The form of water surfaces between soil particles.** — In the case of a soil, however, the question of the capillary film becomes more complex, since a great number of different-sized particles are present in more or less close contact with one another. This means that under normal soil conditions the capillary film is continuous from one particle to another — a very different question to consider from that of a film about a single isolated soil grain more or less spherical in shape. Suppose, for example, that two particles, each carrying a capillary water film, be brought into such contact that the films coalesce. There are now two distinct surfaces — that at A, A' (see Fig. 32), with the curvature of the original film, and that at B, which is very acute and which naturally must exert a very great outward pull. Under the stress of this pull developed by the surface tension acting in this film of very great curvature,

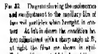

FIG. 32. — Diagram showing the coalescence and readjustment of the capillary film of two soil particles when brought in contact. At left is shown the condition before adjustment with a sharp angle at B, at right the films are shown in equilibrium with a great thickening at B.

the water is drawn into the space between the particles, where it becomes thicker than the capillary film about the particles. This readjustment continues until the forces developed by the two films become equal. An equilibrium is now established. It is evident, then, that as the capillary water becomes less in a soil from any cause, the moisture collected in the spaces between the particles becomes less and less, but still remains thicker than the films about the particles themselves. What percentage of the capillary water is held in the thickened waists of the soil grains cannot be calculated, but it is probable that this moisture makes up the major part of the capillary water of any soil. One of the errors in the determination of the hygroscopic coefficient of a soil, as already pointed out, arises from the tendency toward the formation of capillary water in these angles between the soil particles before the hygroscopic film on the grains themselves becomes satisfied.

142. Factors affecting amount of capillary water. — As might naturally be expected, the factors that tend to vary the amount of capillary water in a soil are several, and their study is more or less complex, due to the secondary influences that they may generate. These factors may be discussed under four heads: (1) surface tension, (2) texture, (3) structure, and (4) organic matter.

143. Surface tension and the amount of capillary water. — Any condition that will influence surface tension will obviously influence the thickness of the capillary film, because of a variation in the forces thereby developed. A rise in temperature, by lowering the surface tension, would consequently lower the capillary capacity of the soil, and if the soil were capillarily saturated would allow some of the water to become gravitational in its

nature. A lowering of the temperature would cause a change in the opposite direction. This theory has been verified by certain experiments by King,[1] in which he found, other conditions being constant, a very decided influence on capillary water through change of temperature. Wollny[2] has shown that a depression of from .85 per cent in sand to as high as 3.7 per cent in kaolin may occur from a rise in temperature of twenty degrees. The surface tension of a liquid may also be greatly changed by the addition of salts, and, since the soil always carries some material in solution, the surface tension, and consequently the capillary capacity, might be expected to increase. As a matter of fact, the soil solution is very dilute, and even if large amounts of fertilizer salts were added the adsorptive power of the soil would tend to maintain a very dilute soil water at the surface of the films. Again, as humus decay is continuously going on, oily materials are probably produced which would tend to spread over the capillary films and greatly reduce their surface tension. Therefore, as far as is now known of the two varying influences, temperature change is by far the most potent in its influence on capillary capacity.

144. Texture and the amount of capillary water. — The finer the texture of a soil, the greater is the number of angles between the particles in which a film of capillary water may be held; also, the actual amount of surface exposed by the particles is immensely larger than in a

[1] King, F. H. Fluctuations in the Level and Rate of Movement of Ground Water. U. S. D. A., Weather Bur., Bul. 5, pp. 50-61. 1892.

[2] Wollny, E. Untersuchungen über die Wasserkapazität der Bodenarten. Forsch. a. d. Gebiete der Agri.-Physik, Band 8, Seite 364-378. 1885.

coarse soil. Due to these two conditions, a soil of fine texture will contain considerably more capillary water than one of which the texture is coarse. The maximum capillary capacity of a soil is not directly proportional to the surface, as was roughly proved to be the case with the hygroscopic coefficient. This is probably because the angle exposures between the grains increase in number as the texture becomes finer much faster than the actual surfaces developed by the particles are generated. The capillary water in any soil varies with the height of the column. This comes about from the gravity effects on the liquid surrounding the particle. If the liquid had no weight, gravity would not be a factor and the same thickness of film would be found at any point in a soil column. Such a condition would greatly simplify the study of soil moisture. If a number of particles (see Fig. 33) carrying maximum capillary films are brought together vertically, the weight of the whole connecting film is thrown momentarily on the capillary surfaces at the top. The capillary spaces at this point immediately lose water downward, so that they may assume a greater curvature and thus support this extra weight thrown on them. This curvature must be sufficient to balance the curvature pressure of the particles below plus the weight of the water in the connecting films. The particles beneath are at the same time undergoing a similar adjustment with a set of particles still farther below, losing water in order to allow a change of

FIG. 33. — Diagram showing the adjustment of the capillary films in a long column and the appearance of free or gravitational water if the weight is too great for the supporting films.

curvature. A thinning of these films results, but not to such an extent as in the particles above. The action continues in this manner through each capillary surface until equilibrium is established, the change in thickness of film being less and less in each case due to the cumulative support of the films above. If the amount of capillary water present is too great to be supported by the films, enough is lost by gravity at the bottom to bring about an equilibrium. The film is at its maximum at the bottom of the column, but decreases in thickness as the column is ascended, not only on the particles themselves, but in the angle interstices as well. This is necessary, as each successive film must support an increased weight of water. It is, therefore, evident that it is impossible to assign any definite figure as to the capillary water capacity of a soil. Only relative or comparative data may be quoted. The following diagram

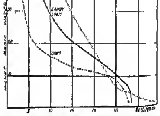

FIG. 56.—Diagram showing the distribution of moisture in capillary columns of soil of different textures. The end of each soil column rests in free water.

(see Fig. 34) from Buckingham[1] makes clear not only the influence of texture on capillary water, but also the distribution of water in a capillary column.

The final mean water content of these soils was 10, 15, and 20 per cent, respectively, for the fine sand, the sandy loam, and the clay; showing that as the texture becomes finer, the greater is the average capillary content even after allowing for the differences in hygroscopic moisture.

145. Effect of structure on the amount of capillary moisture. — The structure of the soil, or, in other words, the arrangement of the particles, will become a factor in capillary capacity in so far as it affects the amount of effective capillary surface. Any arrangement of particles that will increase the number of angles of contact will evidently increase the amount of capillary water. The compacting of a loose soil will increase the possible capillary moisture until all the interstitial space becomes capillary in its nature; further compacting will then cause a marked decrease. The granulation of a clay soil, by producing a crumb structure and by actually increasing the effective surface exposure, tends to increase its water-holding capacity. At the same time the compacting of a sand, by increasing not only the actual effective surface, but also the number of angles possible for capillary concentration, will cause a rise in the capillary capacity of that soil.

In a study of this kind it is very evident that the average data of a long column should be considered, since the percentage of moisture at any one point is not indicative of the true capillary capacity of a soil. Such

[1] Buckingham, E. Studies on the Movement of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 38, p. 32. 1907.

figures have been obtained by Buckingham[1] in his study of loose and compact soils. The following curves represent the general trend of his results: —

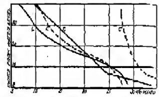

FIG. [illegible]. — Diagram showing the effect of compaction upon the distribution of moisture in capillary columns. (L), loose sandy loam; (L'), compact sandy loam; (C), compact clay; (C'), loose clay.

While it is evident that the mean water content of the compact sandy loam is greater than that of the less compact, the latter showed a higher percentage of moisture up to about the tenth inch. The clay shows a more marked effect from compacting, dropping in the compact sample almost as low as the sand, on the average, and showing at about ten inches from the end of the column a percentage of moisture considerably below that of either the loose or the compact sand. It is obvious that the farmer may do much in the control of capillary water by promoting a proper physical condition of his soil.

146. Organic matter and the amount of capillary moisture. — Organic matter, especially when it has been reduced to the form of humus, has great capillary capacity, far excelling in this regard the mineral constituents of the soil. Its porosity affords an enormous internal sur-

[1] Buckingham, E. Studies on the Movement of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 38, pp. 14–35. 1907.

face, while its colloids exert an affinity for moisture which raises its water capacity to a very high degree. Its tendency to swell on wetting is but a change in condition incident to an approach to its maximum moisture content. The following data, taken from a compilation by Storer,[1] give an idea of the capillary capacity of the soil organic matter: —

	Percentage of water
1. Humous extract from peat	1200
2. Non-acid extract from peat	165
3. Vegetable mold	309
4. Peat	190
5. Garden loam, 7 per cent humus	96
6. Illinois prairie soil	57
7. Field loam, 3.4 per cent humus	52
8. Mountain valley loam, 1.2 per cent humus .	47

Even after allowance has been made for the increased hygroscopic coefficient incident to an increase in organic matter, the effect of the latter is very strongly evident on the capillary capacity of a soil. Besides this direct effect, organic matter exerts a stimulus toward better granulation, a condition in itself favorable to increased water-holding power.

147. **Determination of capillary water.** — The capillary water in a sample of field soil may be determined by making a moisture test in the ordinary way for the total water contained. This represents the hygroscopic plus the capillary water. A determination of the hygroscopic coefficient on another sample yields a figure which when

[1] Storer, C. H. Agriculture, Vol. I, p. 106. New York 1910.

subtracted from the total water will give the capillary water present in the sample. The capillary water at various points in a soil column may be obtained by subtracting the hygroscopic coefficient from the various percentages of moisture present, since the thin hygroscopic film is not influenced by height of column or ordinary structural conditions. In ordinary soils, however, the differences in hygroscopicity are not so great but that the total water retained in a soil column against gravity serves as a very good measure of relative capillary capacity.

146. The moisture equivalent of soils. — Briggs and McLane[1] have perfected a method of comparing soils on the basis of their capacity to hold water against a definite and constant centrifugal force of one to three thousand times the force of gravity. The soils, in thin layer, are placed in perforated brass cups which fit into a centrifugal machine capable of developing the above force, and are whirled until equilibrium is reached. The resultant moisture percentage is designated as the moisture equivalent. It really represents the capillary capacity of a soil of minimum column length when subject to a constant and known force or pull. The finer the soil, the greater of course is the moisture equivalent. The authors also found that 1 per cent of clay or organic matter represented a retentive power of about .62 per cent, while 1 per cent of silt corresponded to a retention of .13 per cent. Representative data which show the correlation of the moisture equivalent to the textural properties of the various types are given in the table on the following page.

[1] Briggs, L. J., and McLane, J. W. The Moisture Equivalents of Soils. U. S. D. A., Bur. Soils, Bul. 45. 1907.

Soil	Percentage of Organic Matter	Percentage of Sand	Percentage of Silt	Percentage of Clay	Moisture Equivalent
1. Norfolk coarse sand	.9	87.9	7.3	4.8	4.6
2. Norfolk fine sandy loam	1.3	78.4	13.1	8.5	6.8
3. Yazoo loam	1.3	25.8	64.1	10.1	18.0
4. Waverly silt loam	2.0	14.9	62.9	22.2	24.4
5. Houston clay loam	3.7	30.9	42.5	26.6	32.4
6. Houston clay	1.4	10.0	56.6	33.4	38.3

149. **The maximum retentive power of a soil.** — Another determination has been devised by Hilgard[1] and used to considerable extent by other investigators.[2] It is designated as the maximum retentive power of a soil. A small perforated brass cup is used, having a diameter of about 5 centimeters and capable of containing a soil column 1 centimeter in height. A short column is used, since it is only under such conditions that a soil may retain against gravity the greatest amount of water. Also, the soil is able to expand or contract, as the case may be, on the assumption of water until an equilibrium is reached. A filter-paper disk is placed in the metal cup, and the soil is poured in, gently jarred down, and stroked off level with the top of the cup. The cup is then set in water and the soil is allowed to take up its maximum moisture. After draining, the weight of the wet soil plus the cup, together with the weights previously obtained, will allow the calculation of the total water contained by the soil.

150. **Capillary movement.** — It has already been shown how different thicknesses of films on two particles tend

[1] Hilgard, E. W. Soils, p. 209. New York. 1911.
[2] This text, paragraph 131.

to become equal, due to the pulling force developed by the angle of curvature between the particles. It is evident that differences in curvature must be the motive force in the capillary movement of soil water. Let it be supposed, for convenience, that three equal spheres when brought in contact contain unequal amounts of water in the angles of curvature (see Fig. 36). In this case the greater pull would exist at *A*, since the angle here is more acute. Consequently water must move through the connecting film until the pull at *A* and that at *B* become the same. Such an adjustment might go on over a large number of films, and if one end of the column was exposed to an evaporation of just the right rate and the other end was in contact with plenty of moisture, large quantities of water would be pumped by capillarity.

FIG. 36. — Diagram showing the mechanics of the capillary movement of water in soil. The readjustment takes place in the direction of (*A*) due to the high tension developed by the sharp film curvature at this point.

This capillary movement may go on in any direction in the soil, since it is largely independent of gravity; yet under natural field conditions the adjustment tends to take place very largely in a vertical direction. When a soil is exposed to evaporation the surface films are thinned and water moves upward to adjust the tension. This explains why such large quantities of soil water may be lost so rapidly from an exposed soil. Capillary adjustment may go on downward, also, as is the case after a shower. Here the rapidity of the adjustment is aided by the weight and movement of the water of percolation.

The capillary adjustment in a soil may go on under

two conditions: (1) if the soil column is in contact with free water, and (2) if no gravity water is present, the movement being merely from a moist soil to a drier one, an inexhaustible supply of water not being present. In the first case the lower portion of the soil is entirely saturated for a short distance above the free water surface, due to the functioning of the pore spaces as true capillary tubes; above this the film movement becomes dominant. The second condition of capillary adjustment is the one most commonly found in a normal soil, since a water table a short distance below the surface is not usually conducive to the best crop growth. In studying the rate and height of capillary rise in any soil, however, the maintenance of a supply of free water at the lower end of the column is usually provided for, since this allows a near approach to the maximum capillary capacity for any point in the column.

161. **Factors affecting rate and height of capillary movement.** — To persons familiar with the habits of growing plants it is evident that capillary movement must play an important part in their nutrition, since the rootlets are unable to bring their absorptive surfaces in contact with all the interstitial spaces where the bulk of the available water is held. Consequently a consideration of the movement of capillary moisture is necessary, not only as to its mechanics, but also as to the factors influencing its rate and height of movement. These factors are four in number: (1) thickness of water film; (2) surface tension; (3) texture, and (4) structure.

162. **Effect of thickness of water film on capillary movement.** — It has been repeatedly noticed, in the study of the capillary adjustment between two soils, that the lower the percentage of water, the slower is the rate

of movement. This indicates that the thickness of the film covering the particles and connecting the interstices containing the bulk of the capillary water is, within certain limits, a dominant factor in rate of movement at least. Let it be supposed that a withdrawal of water occurs at A (see Fig. 37), the interstitial space between two particles, the water surface being represented by the dotted line aa'. There is an immediate increase in the curvature of this surface, and water tends to flow through the capillary film spaces at c and c', toward this area of greater tension. If water continues to be withdrawn at A, this adjustment continues with considerable ease until the film channel at c and c' becomes so thin as to cause its surface (bb') to approach the edge of the hygroscopic film surrounding the particle. The viscosity of the water gradually becomes a factor at this point, impeding the capillary adjustment toward A. This point of sluggish capillary movement has been designated by Widtsoe[1] as the point of lento-capillarity.

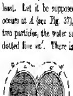

FIG. 37. – Diagram for the explanation of the effect of thickness of water film about soil particles upon rate of capillary movement.

The amount of capillary water delivered at any one point, therefore, will obviously be influenced by the thickness of the film and may consequently be taken as a measure of rate of rise. A short soil column should deliver more water from a constant source than a longer one, due to the thicker films at the sur-

[1] Widtsoe, J. A., and McLaughlin, W. W. The Movement of Water in Irrigated Soils. Utah Agr. Exp. Sta., Bul. 115, pp. 223–271. 1912.

face of the former column. King[1] shows this by the following data: —

EVAPORATION FROM THE SURFACE OF SAND COLUMNS OF DIFFERENT LENGTHS, THEIR BASE BEING IN CONTACT WITH FREE WATER

LENGTH OF COLUMN IN INCHES	EVAPORATION AT SURFACE IN INCHES A DAY
6	.114
12	.111
18	.080
24	.089
30	.019

Briggs and Lapham[2] found, in comparing the evaporation from tubes of different lengths (85 and 165 centimeters, respectively) of Sea Island soil, that the shorter column showed over five times as much evaporation in a period of forty-two days. This diminished flow with the thinner films is a vital point in plant production, since wilting must occur as soon as capillary movement becomes too sluggish to supply moisture fast enough for normal development.

The thickness of film is important also in a consideration of the height of rise in dry and moist soil respectively. It is evident that the rate would be much more rapid in the latter, but what as to total rise? Stewart,[3] in study-

[1] King, F. H. Principles and Conditions of the Movements of Ground Water. U. S. Geol. Sur., 19th Ann. Rept., Part II, p. 92. 1897-1898.

[2] Briggs, L. J., and Lapham, M. H. Capillary Studies. U. S. D. A., Bur. Soils, Bul. 19, pp. 24-25. 1902.

[3] Reported by Briggs, L. J., and Lapham, M. H. Capillary Studies. U. S. D. A., Bur. Soils, Bul. 19, p. 20. 1902.

ing the capillary limits as to the height of rise in dry and moist Michigan soils, found this limit much greater where the soil was damp. This vertical rise from a water table was almost three times greater, on the average, in the soil in which the films were originally thicker. Briggs and Lapham[1] found this ratio in Sea Island soil to be as high as four and one-half; while Wollny[2] has shown sand with 9.5 per cent of moisture to raise moisture from a water table one-half higher in six days than did the same sand dry. It is evident, therefore, that a soil with a thick capillary film will carry moisture faster than one with a thinner film, and also will raise the moisture higher when the final film adjustment has taken place.

In an air-dry soil it is obvious that before capillarity may take place a thicker film than has already existed must be established. This is often difficult because of the presence of oily materials deposited on the surface of the particles during the process of drying out. Such a condition probably accounts, at least partially, for the difference in total rise of capillary water in a dry and in a moist soil, since, theoretically, if time enough were given for adjustment, the total height should be the same in both columns. This resistance of dry soil to the resumption of a capillary film is made use of in soil mulches, where a dry surface layer of the soil checks evaporation by impeding capillary rise. It is also obvious that in a study of the rate and height of capillary movement and the factors affecting it, moist columns should be used, as this is a

[1] Briggs, L. J., and Lapham, M. H. Capillary Studies. U. S. D. A., Bur. Soils, Bul. 19, p. 26. 1902.

[2] Wollny, E. Untersuchungen über die Kapillare Leitung des Wassers im Boden. Forsch. a. d. Gebiete d. Agri.-Physik, Band 7, Seite 269-308. 1884.

near approach to the conditions of a field soil. Since this is rather a difficult study to carry out, most of the rate and height data on capillary movement have been largely obtained with dry columns in contact with free water at the bottom. Such data are comparative, but are far from quantitative as regards the performance of any soil under normal conditions.

153. **Surface tension and capillary movement.** — As has already been shown, the thickness of a maximum capillary film is largely determined by surface tension; and as surface tension with any given curvature exerts a definite pressure, it is evident that this pressure may become greater or smaller with variations in the surface tension. One of the most potent factors having to do with this variation is temperature. If the temperature of a soil column in capillary equilibrium and containing its maximum capillary moisture should be raised, some of the water would be lost as free water, since the pulling power of the films would be decreased. In the same way, the capillary capacity would be increased by a lowering of the temperature, which of course would mean a higher capillary rise in either a dry or a wet soil. The rate of movement,[1] however, would be facilitated in the first case, since the viscosity of the water would be much reduced, allowing the movement in the film channels to take place with less friction.

King[2] has verified these conclusions in his experiments

[1] Wollny, E. Untersuchungen über die Kapillare Leitung des Wassers im Boden. Forsch. a. d. Gebiete d. Agri.-Physik, Band 8, Seite 206–220. 1885.

[2] King, F. H. Fluctuations of the Level and Rate of Flow of Ground Water. U. S. D. A., Weather Bur., Bul. 5, pp. 59–[illegible]. 1892.

with the fluctuations of the ground water of a soil held in a large cylindrical tank. He found that with a lowering of temperature the ground water was lowered, due to the increased capillary capacity of the soil generated by a higher surface tension. A consequent upward movement of water took place. When the temperature was raised, however, there was a reverse movement, due to a change of capillary water to free water brought about by a lowered surface tension.

The surface tension may also be varied by materials in solutions, most salts tending to cause increased tension. The addition of soluble fertilizer salts to a soil would therefore be expected to exert some influence. It must be remembered in this connection that all soils contain a certain amount of oily substances, produced during the processes of organic decay. It is probable that the lowering effect of such material would largely overbalance any marked influence from fertilizer salts. Moreover, as such salts are strongly adsorbed by the soil particles, their effect on the concentration of the surface film would probably be slight even if undisturbed by the soil resins. Wollny[1] has shown that adsorbed salts produce little effect on capillarity, while non-adsorbed salts cause a depression increasing with concentration.

Briggs and Lapham[2] found that with Sea Island soil dissolved salts in dilute solution had no appreciable effect except in the case of sodium carbonate. The increased rise in this case they ascribe to the saponification of the

[1] Wollny, E. Untersuchungen über die Kapillare Leitung des Wassers. Forsch. a. d. Gebiete d. Agri.-Physik, Band 7, Seite 269-308. 1884.

[2] Briggs, J. R., and Lapham, M. H. Capillary Studies. U. S. D. A., Bur. Soils, Bul. 19, pp. 5-18. 1902.

oils on the particles, and a subsequent exposure of clean surfaces for capillary movement. These authors found also that concentrated solutions reduced the rate of capillary movement. Davis,[1] in working with a silt loam, obtained variable results, some salts depressing and some accelerating capillary rise. Potassium acid phosphate caused the maximum retardation, while ammonium nitrate most markedly increased the rate. Since only one soil was used and the greatest observed capillary rise was less than twelve inches, additional data must be presented before it is clear that the concentration of salts may become a very important factor in humid soils. In alkali soils, in which the concentration of the salts is very great, there is no doubt that considerable retardation may occur.

154. Effect of texture on capillary movement. — In soils of fine texture, not only is the amount of film surface exposed greater than in coarse soils, but the curvature of the films is also greater, due to the shorter radii. The effective pressure exerted by the films is consequently much higher in fine-grained soil. The greater exposure of surface and the increased pressure both serve to raise the friction coefficient and retard the rate of flow. The finer the texture of the soil, other factors being equal, the slower is the movement of capillary water. Water should therefore rise less rapidly from a water table through a column of clay than through a sand or a sandy loam.

The height to which water may be drawn by the effective capillary power of a soil, equilibrium being established, depends on the number of interstitial angles. The greater the number of angles, the greater is the total

[1] Davis, R. O. E. The Effect of Soluble Salts on the Physical Properties of Soils. U. S. D. A., Bur. Soils, Bul. 82, pp. 23-31. 1911.

supporting power of the films. As a silt soil contains a larger number of such angles, its capillary pull is greater than that of a sand, and consequently the ultimate movement would be of greater scope. The finer the texture, then, the slower is the rate of capillary movement but the greater is the distance.[1]

The relation of texture to rate and height of capillary movement in dry soil is shown by the following unpublished data, obtained in the laboratory of the Department of Soil Technology, Cornell University:

Effect of Texture on Rate and Height of Capillary Rise from a Water Table through Dry Soil

Soil	1 Hour	1 Day	2 Days	3 Days	4 Days	5 Days
	Inches	Inches	Inches	Inches	Inches	Inches
Sand	3.5	5.0	5.9	6.8	6.8	6.0
Clay	.5	5.7	8.0	10.9	13.2	13.3
Silt	2.6	14.5	20.6	24.2	26.2	27.4

It is seen that the movement in sand is rapid, one-half of the total rise being attained in one hour. The maximum height is reached in about three days. The silt in this case seems to be of just about the right textural condition for a fairly rapid rise, yet it exerts enough capillary pull to attain a good distance above the water table. The friction in the clay is greater, however, and this results in a slower rate. Whether the clay would ever be able to exhibit a rise comparable with its tremendous pull-

[1] Wollny, E. Untersuchungen über die Kapillare Leitung des Wassers im Boden. Forsch. a. d. Gebiete d. Agri.-Physik, Band 7, Seite 269–308. 1884. Also, Forsch. a. d. Gebiete d. Agri.-Physik, Band 8, Seite 206–220. 1885.

ing capacity is doubtful, because of the resistance offered by the dry soil.

155. **Texture and the capillary pull of soils.** — An ingenious method for measuring quantitatively the capillary pull exerted by a moist soil has been devised by Lynde and Dupré.[1] The apparatus consists of a glass funnel joined to a thick-walled capillary tube by means of a piece of rubber tubing, a water seal being used at this point. The lower end dips into mercury. The soil to be studied is placed in the funnel, and after being saturated is connected by means of a wick of cheesecloth or filter paper to the water column previously established in the capillary tube. If no break occurs between the soil and the capillary water column, the apparatus is ready for use.

The excess water having drained away, there is a thinning of the films on the soil surface due to evaporation. Equilibrium adjustments now take place, which result in the drawing upward of the water column. The mercury follows, and the strength of the pull may be measured by the height of the mercury column. The old method of measuring capillary power by the water movement through a dry soil is vitiated by two conditions — the length of time necessary, and the fact that the maximum lift cannot be obtained due to excessive friction. This new method uses a wet soil, requires only a short time, and gives a more nearly accurate idea of the power of the capillary pull. It does not, however, yield data regarding rate of movement, — a factor of vital importance to plant growth, as will be shown later.

Lynde and Dupré, in their results, confirm the state-

[1] Lynde, C. J., and Dupré, H. A. On a New Method of Measuring the Capillary Lift in Soils. Jour. Amer. Soc. Agron., Vol. 5, No. 2, pp. 107-116. 1913.

ments already made regarding the relation of texture to capillary power:

THE CAPILLARY LIFT OF SOIL SEPARATES AS DETERMINED BY LYDON AND DUPRÉ

SOIL	DIAMETER OF GRAIN, IN MILLIMETERS	LIFT OF WATER COLUMN, IN FEET
Medium sand	.5 -.25	.98
Fine sand	.25 -.10	1.78
Very fine sand	.10 -.05	4.05
Silt	.05 -.005	9.99
Clay	.005-	25.50

The capillary pull may also be established, at least comparatively, by the height of the wetted soil and the amounts of water at various points in a soil column that has reached a capillary equilibrium when its base is in contact with a constant supply of water. The curves from Buckingham[1] (Fig. 34, p. 210) determined after the soil had stood for sixty-eight days, illustrate this.

156. Effect of structure on capillary movement. — Structure has already been shown to affect capillary capacity by its influence on the angle interstices. Evidently, therefore, it may alter both the rate and the height of capillary rise. The loosening of a clay soil or the compacting of a sandy soil will lessen the effective film friction, while at the same time it will strengthen the capillary pull resulting in a faster and a higher capillary flow of water. The exact structural condition of any soil in which this result is realized to its highest efficiency it is impossible to judge exactly. In general, however, the

[1] Buckingham, E. Studies on the Movement of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 38, p. 22. 1907.

point is approached when the soil is in the best physical condition for crop growth. Tillage operations in general, tile drainage, and the addition of lime and organic matter, operate toward this result by their granulating tendencies; while rolling, by compacting a too loose surface, may accomplish the same effect but by an opposite process.

At certain seasons of the year capillarity must be impeded near the surface, as it continually pumps valuable water upward to be lost by evaporation. This movement may be checked by producing on the soil surface, by appropriate tillage, a layer of dry, loose soil. This layer, called a soil mulch, affords much resistance to wetting because of its dryness, while at the same time it affords but little surface and few angle interstices for effective capillary pull. Thus it is that a farmer, in order to meet his immediate or future needs, may alter and control capillary movement by careful attention to physical conditions, especially those at the surface where evaporation is always active.

157. **Gravitational water.** — As soon as the capillary capacity of a soil column is satisfied, further addition of moisture will cause the appearance of free water in the air spaces. By the attraction of gravity, this water moves downward through the earth at a rate varying with soil and climatic conditions. In general the flow is governed by four factors — pressure, temperature, texture, and structure. An understanding of the operation of these forces is important, since the rapid elimination of free water from the soil is necessary for optimum plant growth. The actual procedure, however, is considered under the head of "Land Drainage," a distinct phase of soil management in itself.

158. **Pressure and the movement of gravity water.** — It is very evident that any pressure exerted on a water

column will accelerate the rate of flow. Under normal conditions pressure may arise from two sources, barometric pressure and the weight of the water column. Changes in barometric pressure are communicated to gravitational water through a movement of the soil air. As the mercury column rises, more air is forced into the soil and the pressure on the soil water increases. Such a change has been observed by King[1] to produce as high as a 15 per cent decrease in the flow of drains. King observed also that the level of wells fluctuated from time to time for the same cause. The expansion of the air of the soil due to daily heatings was also observed to produce diurnal oscillations in the level and the rate of flow of ground water.

Perhaps of greater import in the rate of percolation of water is the pressure produced by the weight of the free water column. Working along this line, Welitschkowsky[2] has shown rather conclusively that with an ideal length of column the flow varies directly with the pressure. His ideal column with the sand with which he experimented was 75 centimeters in length. With a longer column the flow did not increase as fast as the pressure; while with a shorter column, doubling the pressure more than doubled the flow. These results have been verified by Wollny[3] and ably reviewed by King.[4]

[1] King, F. H. The Soil, p. 180. New York. 1906.

[2] Welitschkowsky, D. von. Experimentelle Untersuchungen über die Permeabilität des Bodens für Wasser. Archiv f. Hygiene, Band II, Seite 499-512. 1884.

[3] Wollny, E. Untersuchungen über die Permeabilität des Bodens für Wasser. Forsch. a. d. Gebiete d. Agri.-Physik, Band 14, Seite 1-28. 1891.

[4] King, F. H. Principles and Conditions of the Movements of Ground Water. U. S. Geol. Survey, 19th Ann. Rpt., Part II, pp. 67-206. 1897-98.

159. **Effect of temperature on the flow of gravity water.** — A rise in temperature of the soil not only varies the amount of capillary water and thus increases the possible free water present, but at the same time it increases the fluidity and thus facilitates percolation. The expansion of the soil air also tends to increase such movement. This can be noticed in the operation of a tile drain in early spring as compared with summer conditions. Calculated effects of temperature change have been verified by controlled experimental results.

160. **Effect of texture and structure on the flow of gravity water.** — Of much more practical importance than temperature, in the flow of gravitational water, are the size and the arrangement of the soil particles. In working with sands of varying grades, Welitschkowsky,[1] Wollny,[2] and others have shown that the flow of water varies with the size of particle, or texture. King[3] has demonstrated that in general with such materials the rate of flow is directly proportional to the square of the diameter of the particle. By the use of the effective mean diameter[4] of a sand sample, he was able to calculate a theoretical flow which compared very closely to observed percolations. In sandy soils this law holds in a very general way, but in clays it fails entirely. For instance,

[1] Welitschkowsky, D. von. Experimentelle Untersuchungen über die Permeabilität des Bodens für Wasser. Archiv f. Hygiene, Band II, Seite 499-512. 1884.

[2] Wollny, E. Untersuchungen über den Einfluss der Struktur des Bodens auf dessen Feuchtigkeits- und Temperaturverhältnisse. Forsch. a. d. Gebiete d. Agri.-Physik, Band 5, Seite 167. 1882.

[3] King, F. H. Principles and Conditions of the Movements of Ground Water. U. S. Geol. Survey, 19th Ann. Rept., Part II, pp. 222-224. 1897-98.

[4] This text, paragraph 87.

if such a law was in force a sand having a diameter of .5 millimeter would exhibit a flow 10,000 times greater than that through a clay loam with a diameter, say, of .005 millimeter, whereas the actual ratio, as observed experimentally by King, was less than 200.

Evidently, therefore, while it can be stated as a general thesis that the flow varies with the texture, no governing law can be deduced for soils since structure exerts such a modifying influence. The percolation in a heavy soil takes place largely through lines of seepage, which are really large channels developed by various agencies. If in the drainage of average soil, the farmer depended on the movement of water through the individual pore spaces, the soil would never be in a condition for crop growth. These lines of seepage are developed by the ordinary forces that function in the production of soil granulation, as freezing and thawing, wetting and drying, lime, humus, plant roots, and tillage operations.

A clear understanding of the factors governing the flow of gravitational water is of especial importance in tile drainage operations, particularly regarding the depth of and interval between tile drains. Since percolation is so slow in a heavy soil, it is evident that the tile must be near the surface in order to secure efficient drainage. In a sand the depth may be increased, because of the slight resistance offered to water movement. The depths for laying tile in a heavy soil range from one and a half to two and a half feet, while in a sand the tile may often be placed as deep as four feet below the surface. It is evident also that the less deep a tile drain is laid, the less distance on either side it will be effective in removing the water; consequently on a clay soil the laterals must be relatively close, as compared to the interval generally

recommended for a sandy soil. A rational understanding of the movements of gravitation water is clearly necessary in the installation of tile drains, not only that the system may be fully effective, but also that a minimum effective cost may be realized.

161. Determination of the quantity of free water that a soil will hold. — While there is no particular advantage in finding the quantity of gravitational water that a soil will hold, since a normal soil should never remain saturated for any length of time, it is nevertheless of interest to know by what methods such data may be obtained. One method is to saturate a column of known weight, and then, by exposing it to percolation, measure the amount of water that is lost. The gravitational water can then be expressed in terms of dry soil. The disadvantage in this method lies in the fact that it is extremely difficult to free a soil entirely of air, so that a determination made in this way would yield low results. Again, a very long time must elapse before a soil will give up all its gravitational water. King[1] found that with even a sand the draining-away of the free water continued over a space of two and one half years. It must also be noted here that because of the lessening of the capillary water as a column of soil is ascended, the space for possible free water increases, thus accounting for the ready entrance of rain into a soil which on the average may contain a relatively high water content.

162. The calculation of the free water of a soil. — A more nearly accurate idea of the possible free-water capacity of soil may be obtained by calculation. If the absolute and the apparent specific gravity of a soil, and

[1] King, F. H. Physics of Agriculture, pp. 134–136. Published by the author, Madison, Wisconsin. 1910.

its percentage of moisture when capillarily satisfied, are known, the following formulas may be used: —

$$\left.\begin{array}{l}\text{Percentage of air space when}\\ \quad\text{capillarily saturated}\end{array}\right\} = \left\{\begin{array}{l}\text{percentage of pore space}\\ \quad - (\text{percentage of } H_2O\\ \quad \times \text{ ap. sp. gr.})\end{array}\right.$$

$$\left.\begin{array}{l}\text{Percentage of free water pos-}\\ \quad\text{sible}\end{array}\right\} = \left\{\dfrac{\text{percentage of air space}}{\text{ap. sp. gr.}}\right.$$

163. Value of studying flow and composition of gravitational water. — While the determination of the possible free water that a soil will hold is of little real value, a knowledge of its movement and its composition is of vital importance. It has already been shown how the rate of movement of such water is a factor in efficient drainage. The amount likely to be thus lost is of interest in plant production from two standpoints: first, the rôle that water plays as a food and a regulator; and secondly, the losses of nutritive elements that always occur with drainage. It is quite evident that these questions should be studied only on soil in a normal field position. Consequently two methods of procedure are open — the use of an efficient system of tile drains, and the construction of lysimeters.

164. The study of gravity water by means of tile drains. — In the first method an area should be chosen where the tile drain receives only the water from the area in question and where the drainage is efficient. A study of the amounts of flow throughout a term of years will yield much valuable data concerning the factors already discussed. An analysis of the drainage water will throw light on the ordinary losses of plant-food from a normal soil under a known cropping system. The advantage

of such a method of attack lies not only in the fact that a large area of undisturbed soil is considered, but also in the opportunity to study practical field treatments in relation to the movement and composition of drainage water.

165. The lysimeter method of studying gravitational water. — The lysimeter method, however, has been the usual mode of attacking these problems. In this method a small block of soil is used, being entirely isolated by appropriate means from the soil surrounding it. Effective and thorough drainage is provided. The advantages of this method are that the variations found in a large field are avoided, the work of carrying on the study is not so great as in a large field, and the experiment is more easily controlled. One of the best-known sets of lysimeters was that established at the Rothamsted Experiment

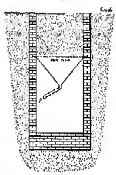

FIG. 38. — Cross section of a lysimeter at the Rothamsted Experiment Station, England. (a), soil column under study; (b), outlet for collected drainage water.

Station[1] in England. (See Fig. 38.) Here blocks of soil one one-thousandth of an acre in surface area were isolated by means of trenches and tunnels, and, supported in the meantime by perforated iron plates, were separated from the surrounding soil by masonry. The blocks of soil were twenty, forty, and sixty inches in depth, respectively. Facilities for catching the drainage were provided under each lysimeter. The advantage of such a method of construction lies in the fact that the structural condition of the soil is undisturbed and consequently the data are immediately trustworthy.

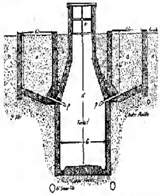

Fig. 39.—Cross section of a soil tank at Cornell University, New York. (s), soil under investigation; (p), outlet of drainage pipe.

[1] Lawes, J. B., Gilbert, J. H., and Warington, R. On the Amount and Composition of the Rain and Drainage Waters Collected at Rothamsted. Jour. Roy. Agr. Soc., Ser. II, Vol. 17, pp. 269-271. 1881.

At Cornell University[1] a system of cement tanks sunk in the ground has been constructed. Each tank is about four and a half feet square and four feet deep. A sloping bottom is provided, with a drainage channel opening into a tunnel beneath and at one side. As the tanks are arranged in two parallel rows, one tunnel suffices for both. (See Fig. 39.) The sides of the tanks are treated with asphaltum in order to prevent solution. The soil must of course be placed in the tanks, this causing a disturbance of its structural condition. As a consequence data as to rate of flow and composition of the drainage water are rather unreliable for the first few years. Such an experiment must necessarily be one of long duration.

166. **Thermal movement of water.** — Little has been said as yet regarding this third mode of water movement, the vapor flow, which is not peculiar to one form of soil water but affects all alike. It is at once apparent that the movement of water vapor can be of little importance within the soil itself, since it depends so largely on the diffusion and convection of the soil air. While the soil air is no doubt practically always saturated with water vapor, the loss of moisture by this means is slight. Buckingham[2] has shown that, while sand allows such a movement to the greatest degree, the loss occurring in a soil with any appreciable depth of layer is almost negligible.

The question of the thermal movement of water at the soil surface, however, is vital in farming operations. At this point the water films are exposed to sun and wind, and drying goes on rapidly, the free, capillary, and a

[1] Lyon, T. L. Tanks for Soil Investigation at Cornell University. Science, N. Ser., Vol. 29, No. 748, pp. 621-623. 1909.

[2] Buckingham, E. Studies on the Movement of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 38, pp. 9-18. 1907.

part of the hygroscopic water vaporizing in the order named. If the loss of the surface moisture were the only consideration, the problem would not be serious; but the capillarity of the soil must be considered also. As the films at the surface become thin a capillary movement begins, and if the evaporation is not too rapid a very great loss of water may occur in a short time.

The evaporation from a bare soil in the Rothamsted lysimeters[1] averaged about seventeen inches a year, with a rainfall ranging from twenty-two to forty-ten inches. This means that from one-third to one-half of the effective rainfall was entirely lost as thermal water. The necessity of checking such a loss becomes apparent, especially in regions where rainfall is slight or drought periods are likely to occur. As no country is free from one or the other of such contingencies, the great prominence that methods of moisture conservation hold in systems of soil management is understandable. While means of checking losses by leaching and run-off are advocated, effective retardation of surface evaporation is always particularly emphasized.

[1] Warington, R. Physical Properties of the Soil, p. 109. Clarendon Press, Oxford. 1900.

CHAPTER XII

THE WATER OF THE SOIL IN ITS RELATION TO PLANTS

WATER, as has already been shown, is one of the external factors in plant growth in that it is necessary in the processes of weathering, which results in the simplification of compounds for plant utilization. It also functions as an internal factor in plant development, inasmuch as it maintains the turgidity of the plant cells, acts as a carrier of food materials, functions as a regulator, and can actually be utilized as a source of hydrogen and oxygen. These direct or indirect relations of water to plant growth may be considered under three heads, as follows: —

167. Relations of water to the plant. —

1. *Water acts as a solvent and a carrier of plant-food materials.* It is therefore a medium of transfer for the mineral and gaseous elements from the soil to their proper places within the plant.
2. *As a food* water either becomes a part of the cell without change, or is broken down and its elements are utilized in new compounds.
3. *Water in maintaining turgidity,* in equalizing the temperature by evaporation from the leaves, and in facilitating quick shifts of food from one part of the plant to another, acts as a regulator during assimilation and while synthetic and metabolic processes are going on.

Soil moisture, therefore, in proper amounts, becomes one of the controlling factors in crop growth and must be looked to before the maximum utilization of the primary elements can be expected. The amount of water held within the plant is not large, however, in comparison with the amount lost by transpiration, although green plants contain from 60 to 90 per cent of moisture. Although the main cause of the high transpiration of most crops is not traceable to the dilute condition of the soil solution, certain regulatory functions may, however, also come into play.

Because of the readiness with which moisture passes from plants into the atmosphere, large quantities of water must be taken from the soil in order that the plant may maintain its proper turgidity. This excess water is largely lost or disposed of by transpiration, at the same time performing its regulatory functions.

158. The water requirement of plants. — As might be expected, the pounds of water transpired for every pound of dry matter produced in the crop is very large. This figure, called the transpiration ratio, or water requirement, ranges from 300 to 500 for crops in humid regions, and almost twice as much for crops in arid climates. An accurate determination of the transpiration ratio of a crop is somewhat difficult, due to the methods of procedure necessary and also to the difficulty of controlling the numerous factors that may vary the transpiration. For really reliable figures the plants must be grown in cans or pots, in order that the water lost may be determined accurately by weighing. If there is no percolation, the water ordinarily lost from a cropped soil includes both that evaporated from the soil surface and that

transpired from the leaves. The former loss may be eliminated from calculations in two ways: (1) by covering the soil in some way so that evaporation is absolutely checked and the only loss is by transpiration, or (2) by determining the evaporation from a bare pot and, by subtracting this from the total water loss from a cropped soil, finding the loss due to transpiration alone.

An objection to the former method is that any covering which interferes with evaporation interferes with proper soil aeration also and may render soil conditions abnormal. In the second method, however, an even more serious error enters, since the evaporation from a bare soil is not the same as that from a soil covered by vegetation because of the shading effects. Also, due to the action of the roots, less water is likely to be allowed to move to the surface by capillary attraction in the cropped soil. Therefore, any data that may be quoted can be only general in its application, not only because of the errors of determination but also because of the great number of factors that under normal conditions may vary the transpiration ratio. The data on the following page, drawn from various investigators working by the general methods[1] already outlined, give some idea of the water transpired by different crops, due allowance being made for various disturbing factors. Below the data regarding transpiration will be found the citations to the work of the various authors as well as a few notes regarding their experimental procedure.

[1] A brief discussion of the various methods is found as follows: Montgomery, E. G. Methods of Determining the Water Requirements of Crops. Proc. Amer. Soc. Agron., Vol. 3, pp. 261–283. 1911. Also Briggs, L. J., and Shantz, H. L., The Water Requirement of Plants. U. S. D. A., Bur. Plant Ind., Bul. 285. 1913.

WATER REQUIREMENTS OF PLANTS BY DIFFERENT INVESTIGATORS

Crop	Lawes[1], Harpenden, England, 1850	Wollny[2], Munich, Germany, 1877	Hellriegel[3], Dahme, Germany, 1883	King[4], Madison, Wisconsin, 1895	Leather[5], Pusa, India, 1911	Briggs and Shantz, Akron, Colo., 1911–1913
Barley	258	774	310	464	468	534
Beans	209	—	282	—		736
Buckwheat		646	363		—	578
Clover	269	—	310	576		797
Maize	—	233	—	271	337	368
Millet	—	447	—	—	—	310
Oats	—	665	376	503	469	597
Peas	259	416	273	477	563	788
Potatoes	—	—	—	385	—	636
Rape	—	912	—	—	—	441
Rye	—	—	353	—	—	685
Wheat	247	—	338	—	544	513

[1] Lawes, J. B. Experimental Investigation into the Amount of Water Given off by Plants during their Growth. Jour. Hort. Soc. London, Vol. 5, pp. 38–63. 1850.

Pots holding 42 pounds of field soil were used. Evaporation from soil was reduced to a very low degree by perforated glass covers cemented on the pots. The figures quoted are from unfertilized soil.

[2] Wollny, E. Der Einfluss der Pflanzendecke und Beschattung auf die Physikalischen Eigenschaften und die Fruchtbarkeit des Bodens, Seite 126. Berlin, 1877.

Wollny grew plants in humous sand in amounts ranging from 5 to 12 kilograms. Evaporation was reduced to a very low degree by perforated covers. Actual evaporation from uncropped cans was observed, however.

[3] Hellriegel, H. Beiträge zu den Naturwissenschaftlichen Grundlagen des Ackerbaus, Seite 663. Braunschweig, 1883.

Hellriegel grew plants in 4 kilograms of clean quartz sand and supplied them with nutrient solutions. The loss by evaporation from uncropped pots was used in determining losses

169. Factors affecting transpiration. — These figures serve to indicate not only the variation between crops, but also the great effect of climate and soil on transpiration.[1] The factors may be listed under three heads, as follows: —

[1] A complete review of the literature concerning the climatic and soil factors in their effect on transpiration may be found as follows: Briggs, L. J., and Shantz, H. L. The Water Requirement of Plants. U. S. D. A., Bur. Plant Ind., Bul. 285. 1913.

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by transpiration. In later experiments covers were used in order to cut down evaporation.

[4] King, F. H. Physics of Agriculture, p. 139. Published by author, Madison, Wisconsin, 1910. Also, The Number of Inches of Water Required for a Ton of Dry Matter in Wisconsin. Wisconsin Agr. Exp. Sta., 11th Ann. Rept., pp. 240–248. 1894, and The Importance of the Right Amount and Right Distribution of Water in Crop Production. Wisconsin Agr. Exp. Sta., 14th Ann. Rept., pp. 217–231. 1897.

King used cans holding about 400 pounds of soil. Some were set down into the earth while others were not. Part of the work was carried on in the field; the remainder was run in vegetative houses. Normal soils were used. Evaporation from soil was very low, water being added from beneath. The data quoted are the average of a large number of tests.

[5] Leather, J. W. Water Requirements of Crops in India. Memoirs, Dept. Agr., India, Chem. Series, Vol. I, No. 8, pp. 133–184, 1910, and No. 10, pp. 205–281. 1911.

Jars containing from 12 to 48 kilograms of soil were used. Loss by evaporation was determined on bare pots. The plants were grown in culture houses or in screened inclosures.

[6] Briggs, L. J., and Shantz, H. L. Relative Water Requirement of Plants. U. S. D. A., Jour. Agr. Research, Vol. III, No. 1, pp. 1–63. 1914. Also, The Water Requirements of Plants. U. S. D. A., Bur. Plant Ind., Bul. 284. 1913.

Plants were grown in cans holding 250 pounds of soil. Evaporation from soil was prevented by means of a paraffin covering. Work was conducted in screened inclosures. The data are the average of several years' work.

1. *Crop.* — Differences due to different crops and to variations of the same crop.
2. *Climate.* — Rain, humidity, sunshine, temperature, and wind.
3. *Soil.* — Moisture and general fertility.

170. Effect of crop and climate on transpiration. — Not only do different crops show a variation of transpiration in the same season, but the same crop may give a totally different transpiration in different years. This is due in part to inherent differences in the crop itself. For example, leaf surface or root zone would totally alter the transpiration relationship under any given condition. However, a great deal of the variation observed in the ratios already quoted arises from differences in climatic conditions. As a general thing, the greater the rainfall, the higher is the humidity and the lower is the relative transpiration. This accounts for the high figures obtained by Widtsoe[1] in arid Utah. Montgomery[2] found, in studying the water requirements of corn under greenhouse conditions, that an increase in the percentage humidity from 42 to 65 lowered the transpiration ratio from 340 to 191. In general, temperature, sunshine, and wind vary together in their effect on transpiration. That is, the more the sunshine, the higher is the temperature, the lower is the humidity, and the

[1] Widtsoe, J. A. Production of Dry Matter with Different Quantities of Irrigation Water. Utah Agr. Exp. Sta., Bul. 116. 1912. Also, Irrigation Investigations. Factors Influencing Evaporation and Transpiration. Utah Agr. Exp. Sta., Bul. 105. 1909.

[2] Montgomery, E. G., and Kiesselbach, T. A. Studies in Water Requirements of Corn. Nebraska Agr. Exp. Sta., Bul. 128, p. 4. 1912.

greater is likely to be the wind velocity. All this would tend to raise the transpiration ratio.

171. Effect of soil moisture on transpiration. — From the soil standpoint, however, the factors inherent in the soil itself are of more vital importance as regards transpiration, since they can be controlled to a certain extent under field conditions. An increase in the moisture content of a soil usually results in an increased transpiration ratio. The work of Hellriegel[1] with barley grown in quartz sand containing a nutrient solution may be cited in this regard, together with the data obtained by Montgomery[2] at Lincoln, Nebraska, with corn grown in a loam soil: —

EFFECT OF SOIL MOISTURE ON TRANSPIRATION

Barley — Hellriegel		Corn — Montgomery	
Soil Moisture Percentage of Total Capacity	Transpiration Ratio	Soil Moisture Percentage of Total Capacity	Transpiration Ratio
80	277	100	290
60	240	80	368
40	216	60	339
30	223	45	293
20	168	35	272
10	180		

These data show clearly that an excessive amount of water in the soil is not a favorable condition for the

[1] Hellriegel, H. Beiträge zu den Naturwissenschaftlichen Grundlagen des Ackerbaus, Seite 659. Braunschweig. 1883.

[2] Montgomery, E. G. Methods of Determining the Water Requirements of Crops. Proc. Amer. Soc. Agron., Vol. 3, p. 276. 1911.

economic use of water, as the plant, in order to supply itself properly with food, must transpire excessive amounts of water. As soil moisture may be controlled, this waste may to a certain extent be eliminated.

172. **The influence of fertility on transpiration.** — The amount of available plant-food is also concerned in the economic utilization of water. In general the data along these lines show that the richer the soil, the lower is the transpiration ratio. Therefore a farmer, in raising the general fertility of his soil by drainage, lime, good tillage, green manures, barnyard manures, and fertilizers, provides at the same time for a greater amount of plant production for every unit of water utilized. Again, quoting from Hellriegel and Montgomery, the following figures are available: —

EFFECT OF THE SUPPLY OF PLANT-FOOD MATERIALS ON THE TRANSPIRATION RATIO OF BARLEY GROWN IN QUARTZ SAND WITH A NUTRIENT SOLUTION; CALCIUM NITRATE BEING IN THE MINIMUM. HELLRIEGEL[1]

UNITS[2] OF $Ca(NO_3)_2$ ADDED	DRY MATTER PRODUCED PER POT (GRAMS)	TRANSPIRATION RATIO
0	1,111	724
4	8,479	309
8	13,336	347
12	18,288	345
16	23,026	302
20	25,404	282

[1] Hellriegel, H. Beiträge zu den Naturwissenschaftlichen Grundlagen des Ackerbaus, p. 628. Braunschweig. 1883.

[2] A unit of $Ca(NO_3)_2$ equals 1 mg.-equivalent. A mg.-equivalent of $Ca(NO_3)_2$ equals 82.1 mg.

RELATIVE WATER REQUIREMENTS OF CORN ON DIFFERENT TYPES OF NEBRASKA SOILS, 1911. MONTGOMERY[1]

SOIL	DRY WEIGHT OF PLANTS IN GRAMS PER POT		TRANSPIRATION RATIO	
	Manured	Unmanured	Manured	Unmanured
Poor (15 bushels) . .	370	113	250	549
Medium (30 bushels) .	418	184	241	479
Fertile (50 bushels) . .	472	270	345	392

173. Effect of texture on transpiration. — The effects of texture have been investigated by a number of men, the work of Von Seelhorst[2] and of Widtsoe[3] being perhaps the most reliable. While these investigators found in general that crops on heavy soils exhibited a lower transpiration ratio, hasty conclusions must not be drawn. Since the fine-textured soils contain more plant-food materials, it is probable that this is the balancing factor rather than texture alone.

174. Actual amounts of water necessary to mature a crop. — Although it can be seen from the transpiration ratio that the amount of water necessary to bring an average crop to maturity is very large, a concrete example may be cited to advantage. A fair estimate of the dry matter produced in raising a forty-bushel crop of wheat would be about two tons. Assuming the transpiration

[1] Montgomery, E. G. Water Requirements of Corn. Nebraska Agr. Exp. Sta., 25th Ann. Rept., p. xi. 1912.

[2] Seelhorst, C. von. Über den Wasserverbrauch von Roggen, Gerste, Weizen, und Kartoffeln. Jour. f. Landwirtschaft, Band 54, Heft 4, Seite 316-342. 1906.

[3] Widtsoe, J. A. Irrigation Investigations. Factors Influencing Evaporation and Transpiration. Utah Agr. Exp. Sta., Bul. 105. 1909.

ratio to be 300, the amount of water actually used by the plant would amount to 600 tons to the acre, or about 5.2 inches of rainfall. This does not include the evaporation that is continually going on from the soil surface, which might very easily amount to as much more. Moreover, this draft on the soil water is not a uniform one, but increases gradually as the crop develops, until at heading time great quantities must be supplied in a short period. The necessity of moisture conservation in order to meet the plant requirements and preserve its normal development, even in humid regions, becomes obvious.

175. Rôle of capillarity in the supplying of the plant with water. — A query arises at this point regarding the mode by which this immense quantity of water is supplied to the plant. The plant rootlets, especially their absorbing surfaces, are few in number as compared with the interstitial angles that contain most of the water retained in the soil. How, then, does the plant avail itself of water not in immediate contact with its rootlets? This question has been anticipated in the discussion concerning the capillary equilibrium which tends to occur in all soils. As soon as the rootlet begins to absorb at one point, the film in that interstitial angle (see Fig. 36) is thinned. A considerable convexity of the water surface occurs at that point, resulting in a great outward pull which causes the water to move in all directions toward that point. Thus, a feeding rootlet, by absorbing some of the soil solution with which it is in contact, creates a condition of instability which results in considerable film movement. It can therefore be said that capillarity is the important factor in any soil in supplying the plant with proper quantities of moisture.

Many of our early investigators have overestimated

the distances through which this movement may be effective in properly supplying the plant.[1] It must be understood, however, that the rate of water supply is the controlling factor in plant nutrition. It has been shown also that the longer the capillary column, the less is the amount of water delivered from a water table to any given point. Therefore capillarity, although it may act through a distance of ten feet, may be important for only three feet as far as plant nutrition is concerned, since water beyond that point is moved too slowly to be of any great value in time of need. No reliable data are available as to this particular phase, but the knowledge of the factors governing capillary movement clearly indicates that capillarity of the soil is of greatest importance in a restricted zone immediately around each absorbing root surface.

176. Influence of water on the plant.[2]—In general, as the amount of water available to a crop is increased, the vegetative growth also is increased, the plant becoming more succulent. The percentage of moisture in the crop, even at harvest time, is usually high. Quality practically always suffers with such a stimulation of vegetative activity. This is especially noticeable with such crops as barley and peaches. Shipping qualities also are depressed with increased water, especially if the water available is excessive. With an enlargement of the plant cell a change probably occurs in the cell contents, tending toward a greater susceptibility to disease. Ripening is delayed, tillering is diminished,

[1] Warington, R. Physical Properties of Soil, p. 106. Oxford. 1900.

[2] Mitscherlich, E. A. Das Wasser als Vegetationsfaktor. Landw. Jahr., Band 42, Seite 701-747. 1912.

and the percentage of protein content of the crop is decreased. It is a curious fact, as will be shown later, that many of the general and morphological effects of large quantities of available water on plant growth are the same as those from the presence of too much soluble nitrogen. In cereals the stimulation of increased water is shown especially in the ratio of grain to straw. Widtsoe's[1] results in this regard are representative of the data[2] available on this point: —

DISTRIBUTION OF DRY MATTER BETWEEN GRAIN AND STRAW WITH VARYING AMOUNTS OF WATER

INCHES OF WATER	GRAIN IN PERCENTAGE OF TOTAL DRY MATTER
5	44.4
7½	43.2
10	42.8
15	40.8
25	38.6
35	37.5
50	32.9

As a general rule this depression of the ratio of grain to straw is not due to an actual decrease in the grain, but to a correspondingly greater production of dry matter in

[1] Widtsoe, J. A. The Production of Dry Matter with Different Quantities of Irrigation Water. Utah Agr. Exp. Sta., Bul. 116, p. 49. 1912.

[2] Bürger, H. Über den Einfluss Verschieden Hohen Wassergehalts des Bodens in den Einzelnen Vegetationsstadien bei Verschiedenem Nährstoffreichtum auf die Entwicklung der Haferpflanzen. Landw. Jahrb., Band 35, Seite 941-1051. 1906. Also, Seelhorst, C. von, und Freckmann, W. Der Einfluss des Wassergehaltes des Bodens auf die Ernten und die Ausbildung Verschiedener Getreidevarietäten. Jour. f. Landw., Band 51, Seite 253-269. 1903.

the vegetative parts. As available water increases this dry matter ascends until a maximum is reached. The general relationships are well exemplified by data from

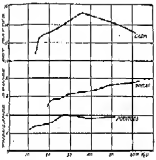

Fig. 40. The effect of increased water supply on the production of dry matter by various crops.

Widtsoe,[1] tabulated on the following page, although other equally valuable figures may be obtained from Von Seelhorst[2] and Atterberg.[3] The curves above (Fig. 40) illustrate Widtsoe's data and the general trend in the dry matter produced as the moisture is increased.

[1] Widtsoe, J. A. The Production of Dry Matter with Different Quantities of Irrigation Water. Utah Agr. Exp. Sta., Bul. 116, pp. 10-25. 1912.

[2] Seelhorst, C. von, und Krzymowski, Dr. Versuch über den Einfluss, welchen das Wasser in den verschiedenen Vegetationsstadien des Hafers auf sein Wachstum ausübt. Jour. f. Landw., Band 53, Seite 357-370. 1905. Also, Atterberg, A. Die Variationen der Nährstoffgehalte bei dem Hafer. Jour. f. Landw., Band 49, Seite 97-113. 1901.

CROP YIELD IN POUNDS TO THE ACRE AS INFLUENCED BY DIFFERENT AMOUNTS OF WATER. WIDTSOE

INCHES OF WATER	DRY MATTER WHEAT	INCHES OF WATER	DRY MATTER CORN	INCHES OF WATER	DRY MATTER POTATOES
16.74	4,969	13.04	10,757	11.17	2111
21.24	5,545	15.54	12,762	13.67	2730
23.74	5,651	20.54	13,082	16.17	2823
28.74	6,270	25.54	13,856	21.17	3406
38.74	6,672	30.54	14,006	26.17	4005
48.74	7,229	35.54	15,304	36.17	3600
63.74	7,919	80.54	12,632	51.17	3787

177. Availability of the water in the soil. — From the discussion already presented regarding the forms of water in the soil, the ways in which they are held, and their movements, it is evident that all the moisture present in a soil is not available for plant growth. Three divisions of the soil water may be made on this basis: unavailable, available, and super-available.

178. Unavailable soil water. — As has been shown in a previous paragraph, free or capillary water may become of little use to a plant through distance, since capillarity is unable to pump the water fast enough to supply ordinary crop needs. Water near at hand or in the immediate zone of the rootlet may also become unavailable through the obstruction of capillarity, friction instead of distance being the cause in this case. As the rootlet thins the interstitial film at any point, capillarity occurs and water moves toward the absorbing surface. This movement is rapid enough for plant needs until the film about the particles become thin. (See Fig. 37.) As the zone of hygroscopic influence of the particle is approached

the viscosity increases very rapidly and cuts down the capillarity to such a point that the needs of the plant are unsatisfied. Wilting therefore occurs simply because the soil is unable to move the water rapidly enough for crop needs. As the viscosity of the water increases very rapidly after the point of lento-capillarity is reached, the wilting coefficient is a figure somewhat less than the percentage representing the lento-capillarity; also, it is greater than the hygroscopic coefficient, since wilting due to viscosity occurs before it is possible for the film to become thinned to the zone of hygroscopicity. Not only all the hygroscopic water is unavailable, then, but also a certain small quantity of the capillary water lying between the point of wilting and the hygroscopic film. This relationship is shown by data from the work of Heinrich and of Briggs and Shantz; men working at widely different times and under entirely different conditions.

Relation of the Wilting Point to the Hygroscopic Coefficient. (Heinrich)[1]

Soil	Wilting Point	Percentage of Hygroscopic Water
Coarse sandy soil . . .	1.5	1.15
Sandy garden soil . . .	4.6	3.00
Fine humous sand . . .	6.2	3.98
Sandy loam	7.8	5.74
Calcareous soil	9.8	5.20
Peat	49.7	42.30

[1] Heinrich, R. Ueber das Vermögen der Pflanzen den Boden an Wasser zu erschöpfen. Jahresbericht der Agri.-chem., Band 18, Seite 369-372. 1875.

Relation of the Wilting Point to the Hygroscopic Coefficient. Briggs and Shantz[1]

Soil	Hygroscopic Coefficient	Wilting Point
Coarse sand	.5	.9
Fine sand	1.5	2.6
Fine sand	2.3	3.3
Sandy loam	3.5	4.8
Sandy loam	4.4	6.3
Fine sandy loam . . .	6.5	9.7
Loam	7.8	10.3
Loam	9.8	13.9
Clay loam	11.4	16.3

179. The wilting coefficient of plants. — It has been known for many years that the common plants present different capacities for resisting drought. This has usually been ascribed to one or more of three causes: (1) difference in root extensions; (2) difference in ability to become adjusted to a slow intake of water; and (3) difference in pulling power against the viscosity of the water film. The last two capabilities would argue for different wilting coefficients for different crops on the same soil. The most extended work on this subject has been by Briggs and Shantz,[2] who found that the permanent wilting point in a saturated atmosphere is practically the same for all plants. Later Caldwell[3] demonstrated that this

[1] Briggs, L. J., and Shantz, H. L. The Wilting Coefficient for Different Plants and its Indirect Determination. U. S. D. A., Bur. Plant Indus., Bul. 230, p. 65. 1912.

[2] Briggs, L. J., and Shantz, H. L. The Wilting Coefficient for Different Plants and its Indirect Determination. U. S. D. A., Bur. Plant Indus., Bul. 230. 1912.

[3] Caldwell, J. S. The Relation of Environmental Conditions to the Phenomenon of Permanent Wilting in Plants. Physiological Researches, Station N, Baltimore. U. S. D. A., Vol. 1, No. 1. July, 1913.

relationship of the physical constants of the soil to the wilting point depends on the rate at which the plant loses water, showing that the soil factors are not entirely dominant in this respect. This work seemed, nevertheless, to indicate that the conclusions of Briggs and Shantz were correct for plants of humid regions, where the wilting occurred in a saturated atmosphere. If such is the case, it can be accounted for only by the fact that the soil forces in their effect on the wilting point are so powerful as to override any distinguishing characteristics that the plant itself may possess, or at least reduce such an influence within the error of actual experimentation.

180. Determination of the wilting point. — Briggs and Shantz,[1] in their investigations, devised a very accurate method for making determinations of the wilting point. Glass tumblers holding about 250 cubic centimeters of soil in an optimum condition were used. The seeds were placed in this soil, after which soft paraffin was poured over the surface in order to stop evaporation, thus removing this disturbing factor in the capillary equilibrium of the moisture. The seedlings on germination were able to push through the paraffin. While the plants were developing, the tumblers were kept standing in a constant-temperature vat of water in order to prevent condensation of moisture on the inside of the glass. The vegetative room was under temperature control. When definite wilting occurred, as determined in a saturated atmosphere, a moisture test was made on the soil. The resulting figure, within experimental error, represents the wilting point for the soil used.

[1] Briggs, L. J., and Shantz, H. L. The Wilting Coefficient for Different Plants and its Indirect Determination. U. S. D. A., Bur. Plant Indus., Bul. 230, pp. 10-14. 1912.

181. Calculation of the wilting point. — In studying the correlation of this wilting coefficient to soil conditions, Briggs and Shantz[1] advanced the following relationships. Expressed as formulæ they represent methods of at least approximating the wilting point from other soil factors. These formulæ are arranged in the order of their reliability, based on the data obtained by the authors: —

1. $\text{Wilting point} = \dfrac{\text{Moisture equivalent}}{1.84}$ (error 2.9 per cent)

2. $\text{Wilting point} = \dfrac{\text{Hygroscopic coefficient}}{.68}$ (error 7.1 per cent)

3. Wilting point $= \dfrac{\text{Water-holding capacity (Hilgard method)} - 21}{2.9}$ (error 8.3 per cent)

182. Relation of texture to the wilting point. — From the data already quoted[2] from Heinrich and from Briggs and Shantz regarding the hygroscopic coefficient and the wilting point, it is evident that a very close relationship exists between the texture of the soil and the percentage of moisture at which plants wilt. The finer the soil texture, the higher is the wilting point. The following figures, from Briggs and Shantz,[3] bring out the point very clearly: —

[1] Briggs, L. J., and Shantz, H. L. The Wilting Coefficient for Different Plants and its Indirect Determination. U. S. D. A., Bur. Plant Indus., Bul. 230, pp. 56–77. 1912.

[2] This text, paragraph 178.

[3] Briggs, L. J., and Shantz, H. L. The Wilting Coefficient for Different Plants and its Indirect Determination. U. S. D. A., Bur. Plant Indus., Bul. 230, pp. 20–33. 1912.

RELATION OF TEXTURE TO THE WILTING POINT OF KUBANKA WHEAT

SOIL	MOISTURE EQUIVALENT	WILTING POINT OF KUBANKA WHEAT
Sand	1.55	.86
Fine sand	4.05	2.00
Fine sand	5.50	3.33
Fine sand	6.74	3.70
Sandy loam	9.70	4.80
Sandy loam	14.50	9.60
Sandy loam	18.60	8.84
Loam	24.80	12.40
Loam	25.00	13.00
Clay loam	27.40	14.60
Clay loam	29.30	17.10

Briggs and Shantz have attempted to express this correlation by a formula which, while very inaccurate, shows in general the relationships already expressed. The correlation in this case is made between the wilting point and the mechanical composition of the soil: —

Wilting point = .01 sand + .12 silt + .57 clay (error 10 per cent)

183. **Available and super-available water.** — Advancing from the wilting, or critical, moisture content of a soil, all the remaining capillary water is found to be available for normal plant use. However, when free water begins to appear, a condition adverse to plant growth is established, and as the saturation point is approached this condition becomes more adverse. This free water is designated as the super-available water, since it is beyond the available and its presence generates conditions unfavorable to plant growth. The upper limit of

the capillary water is called the maximum water content for plant growth. The bad effects of free water on the plant arise largely from the poor aëration that results from its presence. Not only are the roots deprived of their oxygen, but toxic materials tend to accumulate. Favorable bacterial activities, such as nitrification and ammonification, are much retarded also.

The various forms of water in the soil and their availability to the plant are illustrated diagrammatically in the following figure.

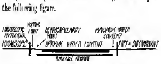

Fig. 42.—Diagram showing the forms of water in the soil and their relationship to the plant.

184. Optimum moisture for plant growth.—It is very evident that there must be some moisture condition of a soil which is best for plant development. This is usually designated as the optimum content. It is not to be assumed, however, that the total range of the available soil water represents this condition for optimum plant growth. Nor is this optimum water content in any particular soil to be designated by a definite percentage. In reality the moisture in a soil may undergo considerable fluctuation and yet allow the plant to develop normally. This is because the physical condition of the soil changes with varying water content and the plant is able to accommodate itself to such a fluctuation without a disturbance in its normal development occurring. Wollny[1] has shown that the optimum moisture for com-

[1] Wollny, E. Untersuchung über den Einfluss der Wachsthumsfaktoren auf das Produktionsvermögen der Kultur-

mon field crops in general covers a range from 60 to 80 per cent of the water capacity of the soil. Mayer[1] placed the optimum moisture content of wheat at 80 per cent of the water capacity of the soil, rye at 75 per cent, barley at 75 per cent, and oats at from 85 to 90 per cent. Such estimates not only emphasize the range of optimum moisture conditions, but at the same time show the relatively high percentage of moisture necessary for maximum crop growth.

Granulation has considerable influence on the range of optimum moisture conditions, since the better the granulation, the better is the soil able to accommodate itself to changes in water content without disturbance of plant growth. The poorer the tilth of any soil, the narrower does this fluctuating in optimum moisture become. In moisture conservation and control a granular soil is one of the first improvements to be aimed at. Drainage, liming, addition of organic matter, and tillage, by leading up to such a condition, increase the effectiveness and economy of utilization of soil moisture.

pflanzen. Forsch. a. d. Gebiete d. Agri.-Physik, Band 20, Seite 53–100. 1897.

[1] Mayer, A. Über den Einfluss kleinerer oder grösserer Mengen von Wasser auf die Entwickelung einiger Kulturpflanzen. Jour. f. Landw., Band 46, Seite 167–184. 1898.

CHAPTER XIII

THE CONTROL OF SOIL MOISTURE

In the discussion of the water requirements of plants, it was apparent that for a normal yield of any crop the amount used by the plant alone was very great, varying from five to ten acre inches according to conditions. Were this the only loss of water, the question of raising crops with given amounts of rainfall would be a simple one. Three further sources of water loss, however, are usually found functioning in the soil and tending to lower the water that would go toward transpiration, a loss absolutely necessary for proper plant growth. The various ways by which water finds an exit from a soil are (1) transpiration, (2) run-off over the surface, (3) percolation, and (4) evaporation. The following diagram makes clear their relationships.

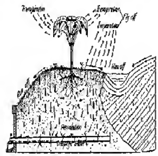

FIG. 43.—Diagram illustrating the ways by which water may be lost from a soil.

It is immediately obvious that as the losses by run-off, leaching, and evaporation increase, the amount of water left for crop utilization decreases. In arid and semiarid regions this is fatal to plant growth, while in humid regions it may be such a factor in periods of drought as to seriously reduce the harvest. Control of moisture is therefore necessary in all regions, and this really consists in so adjusting run-off, leaching, and evaporation as to maintain optimum moisture conditions in the soil at all times. This control should result in a proper and economic utilization of the soil water by the plant.

185. **Run-off losses.** — In regions of heavy rainfall or in areas where the land is sloping or rather impervious to water, a considerable amount of the moisture received as rain is likely to be lost by running away over the surface. Under such conditions two considerations are important. (1) By not entering the soil the water is lost for plant use; and (2) washing of the soil may occur, which if allowed to proceed may entirely ruin the land. The amount of run-off varies with the rainfall, the slope, and the character of the soil. In some regions it may rise as high as 50 per cent of the rainfall, while in arid regions it is of course very nearly zero. As a general thing, this loss is estimated with the losses by leaching, the two being expressed as one figure.

186. **Percolation losses.** — When at any time the amount of rainfall entering a soil becomes greater than the water-holding capacity of the soil, losses by percolation will result. The losses will depend largely on the amount and distribution of the rainfall and the capability of the soil to hold moisture. The bad effects of excessive percolation are twofold: (1) the actual loss of water, and (2) the leaching-out of salts that may function

as plant-food. The quantity of nutrient elements lost annually from the average soil in a humid region more than equals that withdrawn by the crops. The results from the Rothamsted drain gauges[1] from 1871 to 1904, on a clay loam soil of three different depths are interesting as to the light that they afford regarding actual drainage losses:—

	Rainfall	Drainage through Soil			Proportion of Rainfall Draining through Soil		
		Depth in Inches			Per Cent		
		20	40	60	20	40	60
January	2.32	1.82	2.05	1.96	78.5	88.4	84.5
February	1.97	1.42	1.57	1.45	72.2	80.0	73.2
March	1.83	0.86	1.02	0.97	47.0	55.6	53.0
April	1.89	0.50	0.57	0.53	26.5	30.0	28.0
May	2.11	0.48	0.55	0.50	22.7	26.1	23.6
June	2.28	0.55	0.65	0.63	24.0	27.6	26.1
July	2.73	0.69	0.70	0.65	25.3	25.6	23.8
August	2.67	0.62	0.62	0.58	23.2	23.2	21.7
September	2.33	0.83	0.83	0.76	35.6	35.8	32.6
October	3.20	1.85	1.84	1.68	57.8	57.5	52.5
November	2.86	2.11	2.18	2.04	73.7	76.3	71.3
December	2.52	2.02	2.15	2.04	80.3	85.4	81.0
Mean total per year	28.98	13.90	14.73	13.79	48.2	51.0	48.0
Winter, October to March	14.70	10.09	10.81	10.15	68.6	73.5	69.0
Summer, April to September	14.28	3.81	3.92	3.64	26.6	27.4	25.5

The rainfall and relative loss through the 40-inch depth of soil is shown graphically in the following diagram:—

[1] Hall, A. D. The Book of the Rothamsted Experiments, p. 23. London. 1905.

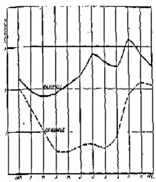

FIG. 43.—Rainfall and percolation losses through a 40-inch soil column. Lysimeter records, Rothamsted Experimental Station, England.

It appears from these figures that about 50 per cent of the rainfall in such a climate as that of England is lost by percolation alone. It appears also that the loss is much lower in summer than in winter, the ratio being about one to three. Also, the longer the soil column, the less is the percolation, due to the greater water-holding capacity possessed by the longer column.

187. **Methods of checking loss by run-off and leaching.**—It must not be inferred that the soil is never in such a condition that percolation, and even run-off, are not advantageous. Often in winter the excess water may be drained over the surface with no damage whatsoever. Also, when the soil becomes filled with free water, either in winter or in the growing season, drainage must take place in order to establish optimum soil conditions. The control of the free water of the soil may be brought

about by drainage operations or by methods that will increase the water-holding capacity of the soil. The former is really a matter of engineering technique and will be treated in a separate chapter. The latter is a function of the soil itself and must be specifically considered at this point.

The necessity of giving attention to losses due to run-off and leaching varies with climatic conditions. In very humid regions these losses are of grave importance, while in arid regions they are insignificant as compared with losses by evaporation. For example, in England the losses by percolation and run-off in many cases are as high as 60 per cent of the rainfall. In the Mississippi River basin the loss is 50 per cent, in the Missouri it is about 20, while in the Great Basin it drops to zero. This does not indicate that drainage is not practiced in the last-named region, however, for, owing to over-irrigation, seepage, and other conditions, drainage operations often become as important as in humid climates.

The quantity of water entering a soil is determined almost entirely by the physical condition of the soil. If the soil is loose and open, the water enters readily and little is lost over the surface as run-off. If, on the other hand, the soil is compact, impervious, and hard, most of the rainfall runs away, and not only is there a serious loss of water, but considerable erosion may also result. The first step in checking run-off losses, therefore, is strictly physical in nature. As the water that has entered the soil moves downward it is continually being changed to capillary water in its passage. If the capillary capacity of the soil is high, a greater percentage of this rain water becomes capillary and a less percentage is left to be carried away as gravitational water. The secret in the control

of run-off and percolation, then, is first, to have a loose, open structure of soil in order to facilitate ready entrance of the water; and secondly, to promote and encourage a physical condition of soil which provides high capillary capacity. Drainage, lime, humus, and good tillage encourage granulation, which has so much to do with the proper entrance of water into the soil and its proper handling and utilization therein. The benefits of drainage are felt only when free water, superavailable to plants, becomes present. Its quick removal, therefore, not only betters the physical condition of the soil, but also aids in the maintenance of the optimum moisture conditions for the plants.

Fall and early spring plowing is always recommended as a means of increasing the moisture capacity of the soil, particularly where organic matter is well supplied. It provides a deep soil, and should establish the best conditions for the storage of moisture, as well as food, for the plant. If organic matter is not supplied, deep plowing is not advisable on light sandy soil; but on clay soil it is beneficial because of the loosening and granulating effect. Fall plowing in particular is to be recommended for such soil, as the loose condition produced facilitates the entrance of surface water while the granulation that the soil undergoes during the winter increases its water-holding power. A soil in excellent physical condition may contain considerably more water than the soil of the same texture but in poor tilth, and yet present better conditions for crop growth. Where fall plowing cannot be done, early spring plowing is the next best procedure.

188. **Evaporation losses.** — Evaporation of soil water takes place almost entirely at the surface, exceptions

being where deep, large cracks occur, which allow thermal loss directly from the subsoil. This loss of water by direct evaporation from the soil may be excessive and may result in direct reduction of the crop yield — a type of loss so familiar that examples hardly need be cited. In the results with the Rothamsted rain gauges about 50 per cent of the annual rainfall was regained in the drainage water. Since the gauges bore no crop, the remaining 50 per cent must have been lost by evaporation. It should be noted that in the summer months under warm temperature this loss was greatest, amounting to 75 per cent of the rainfall. Correspondingly, in the semiarid and arid sections of the country, where there is little or no drainage, the rainfall is all lost by evaporation. Investigations indicate that about 70 per cent of the precipitation on the land surface is derived from evaporation from land surface. Even in humid regions, where the annual rainfall is ample for maximum crop production, the crops are frequently reduced below the profit point by prolonged periods of dry weather in the growing season, during which the loss of water from the plants, coupled with the loss from the soil, exhausts the moisture supply.

While run-off and percolation are directly proportional to the rainfall, loss by evaporation does not vary to such a degree. The loss by percolation depends almost directly upon the amount of rainfall above the retentive power of the soil. In years of heavy precipitation, losses by percolation must increase. Evaporation from the soil depends largely upon the time that the soil surface is moist, and this will not vary markedly from year to year. The following figures from the Rothamsted drain gauges may be quoted in this regard:—

RECORDS FROM ROTHAMSTED (1870-1878)[1]

RAINFALL INCHES	EVAPORATION INCHES	PERCOLATION INCHES
23.9	17.3	5.6
26.3	18.4	7.9
28.3	18.1	11.3
30.8	18.3	12.5
31.6	16.6	15.0
32.6	18.0	14.6
34.2	18.0	16.2
35.8	18.3	17.5
42.7	17.2	25.5

A rough calculation may be made which will show the apportionment of the yearly rainfall in a humid region of the temperate zone between the three forms of losses — run-off and percolation, evaporation, and transpiration. The percolation under a rainfall, say, of 28 inches, as shown by the Rothamsted work, is roughly 14 inches, or 50 per cent. The water requirement of an ordinary crop is about 7 inches. This leaves a loss of 7 inches to be credited to evaporation. In other words, one-half the rainfall goes as run-off and percolation, while the other half is divided about equally between the plant and loss by evaporation. While run-off and percolation may be checked to some extent, not enough conservation can occur in this direction to tide a crop over a period of drought. Paramount attention should therefore be directed toward the checking of losses by evaporation, since moisture thus saved means just that amount added to the water available for crop use. It should be remembered that over a large proportion of cultivated lands

[1] Warington, R. Physical Properties of the Soil, p. 109. 1900.

the crop yields are controlled more directly by lack than by excess of water. It is a common observation that soils which ordinarily give a low yield in seasons of normal or low rainfall give good yields in a wet season, indicating how dominant is this influence of moisture on soil fertility.

189. Methods of checking evaporation losses. — All methods for the reduction or elimination of evaporation losses depend on one or both of two functions: (1) the actual control of evaporation as it occurs at the surface, and (2) the prevention of the movement of capillary water upward to take the place of the moisture already lost. It has been shown that as water is lost at the surface of a soil, movement is induced and capillarity is set up. Such action, if allowed to continue, must ultimately bring about great losses. The obstruction of capillarity would obviously lower these losses to a marked degree. As it is difficult and often impracticable to entirely eliminate evaporation, the most successful methods of water control usually include a change in the structural condition of the soil which tends toward a lower capillarity, especially at the surface. Of all the methods of moisture conservation, the use of a mulch has been found most satisfactory. The consideration of mulches is therefore one of the most important phases in the study of moisture control.

190. Mulches for moisture control. — Any material applied to the surface of a soil primarily to prevent loss by evaporation may be designated as a mulch. It may at the same time fulfill other useful functions, such as the keeping down of weeds and the maintaining of a uniform soil temperature. By the conservation of the moisture, more water remains in the soil for the solution

of the essential elements, and bacterial activity is encouraged. As a general rule, more soluble plant-food is likely to be found under a mulched soil, other conditions being equal, than under a soil not so treated.

191. **Kinds of mulches.** — Mulches are of two general sorts, artificial and natural. In the former case, foreign material is merely spread over the soil surface and evaporation is obstructed thereby. Manure, straw, leaves, and the like, may be used successfully. Such mulches, while very effective, are not generally applicable to field crops where intertillage is practiced, since they would make cultivation absolutely impossible by cumbering the soil surface with a large amount of inert material. Their use is therefore limited to intensive crops such as are found in trucking operations. Leaves, including pine needles, and sawdust are very effective as a mulch, but some precautions should be observed in their application. For example, the oak is rich in tannic acid, which may be washed out of the mulch into the soil and by its effect on the growing plant may cause a lowering of productivity. In some European countries, as well as in a few localities in America, stones have been drawn on the soil to serve as a mulch, particularly in orchard and vineyard culture, with markedly beneficial effects. Particularly is this true on such lands as are too steep to permit cultivation. As further evidence of the utility of this practice, it has been observed in the fruit-growing section of the Ozark Mountains, and doubtless in other regions, that the removal of stones from the land not only results in the soil's becoming harder, but also reduces crop yield by increasing loss of moisture. It is therefore necessary for the farmer to decide whether the inconvenience to tillage or other operations due to the presence of

stones may not be more than offset by their beneficial effects.

The materials for mulching mentioned above are all strictly artificial, and their application is greatly limited, due to the lack of material and the expense involved. They are therefore used only under special conditions. The second type of mulch is almost universal in its practical availability.

By proper cultivation almost any soil surface may be brought into such a condition that evaporation of moisture is more rapid than the upward capillary movement. This is because surface tillage produces a loose, open structure, which, while increasing the rate of thermal movement of the water, at the same time obstructs capillary action. The surface layer, therefore, quickly becomes air-dry and is in a condition designated as a soil mulch. As it differs from the soil below only in structure, it has numerous advantages over artificial mulches, at the same time performing successfully all the functions of the latter. Since not only the water in the mulch is sacrificed but also a small quantity pumped upward by capillarity during the operation, speed in formation is of importance. The tillage implements that give the maximum looseness and granulation will prove the most successful. A spike-tooth harrow or a weeder is the instrument ordinarily employed.

192. The functions of a mulch. — A soil mulch depends for its effectiveness on two functions — (1) the shutting off of evaporation, and (2) the checking of capillary movement upward. It has already been shown that thermal movement of water through dry soil layers is practically nil;[1] therefore, as long as the soil is dry, evaporation is

[1] This text, paragraph 166.

very low. Moreover, any layer of air-dry soil resists wetting, principally because of the resins and oils that become deposited on the surface of the soil particles. This material, called "agricere," has a low surface tension and the capillary water film is not easily resumed under such conditions. Again, if the soil is well granulated it is able to assume a looser and more open structure. The interstitial angles, which afford spaces for capillary surfaces, are cut down, and the capillary pulling power of the layer is much reduced even if it should assume a film of water. It is evident that looseness and dryness are the essentials in the efficiency of a soil mulch. As long as a mulch is dry, texture is not a very important factor in efficiency, a dry sand being about as effective as a dry clay. Texture is important, however, in the length of time that a mulch will remain effective. Due to the fact that the capillary power of a clay is so great, it will become moist from below after a few days, while a sand mulch, if there is no rain, will remain dry for an indefinite period. On a heavy clay soil in fine tilth a mulch may be destroyed by moist, foggy weather, or by a number of days of very humid atmosphere; such a condition, by causing condensation of moisture on the clay, hastens the reëstablishment of capillarity with the subsoil, thus allowing moisture to be pumped up and lost.

198. **The soil mulch *versus* the dust mulch.** A few words will not be amiss at this point regarding the term "dust mulch," which is observed so commonly in soil literature. This term would indicate that the mulch is in a very fine condition, its granulation having been broken down. Such a condition would not be conducive to efficiency, as it would encourage capillarity, while at

the same time it would become puddled on wetting — certainly a very undesirable condition. As a matter of fact, efficient mulches are not in a dust form, but are granulated and much looser than could be obtained were they finely divided. It is evident that the term "dust mulch" is incorrect and should be superseded by "soil mulch," a figure of speech which more exactly expresses the true field conditions.

184. Formation of a mulch. — It has already been stated that a mulch should be formed as quickly as possible. This would not be such a factor were the mulch adjusted only once in a season. It is necessary, however, especially in humid regions, to re-form a mulch every week or ten days. The cutting-down of formation losses therefore becomes important. In general the mulch should be made just as soon after a rain as it is possible to work the land, since the most rapid evaporation occurs during the few hours immediately after a rain, when the soil is very moist. Even after light showers the soil should be quickly cultivated, since the rain may have established a capillary communication with the surface and thus provided for a rapid loss of the water already conserved by previous work. Under arid conditions, where the atmosphere is dry and hot and in free circulation, the surface soil is quickly dried out after a rain. This drying takes place so rapidly that the capillary films quickly become so thin that movement is stopped and no more water is brought to the surface. The soil may be ever so hard and compact, but as long as it is kept dry it very effectively conserves the moisture below. The more rapid the loss, the more quickly will the mulch condition be created, and therefore the less the total loss of water is likely to be. This has been demon-

strated by Buckingham[1] in some experiments in which arid climate conditions were created at the surface of a capillary column forty-six inches in height. The soil was a fine sandy loam. At first the loss of water under the arid conditions was very rapid and exceeded that under the humid conditions; but the rate of loss soon dropped considerably below that of the humid column, and continued to fall behind during the twenty days of the experiment. The differences in this case were due to self-mulching, a very common phenomenon of arid land soils, particularly those of a loamy character. This self-mulching is often seen in sands in humid regions. The under layers of a sand pile are always moist, due to the self-mulching tendencies of the surface. The results of Buckingham are shown in the following curves: —

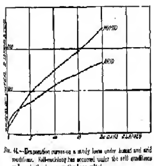

Fig. 41. — Evaporation curves on a sandy loam under humid and arid conditions. Self-mulching has occurred under the arid conditions and a reduction in evaporation has resulted.

[1] Buckingham, E. Studies on the Movement of Soil Moisture. U. S. D. A., Bur. Soils, Bul. 38, pp. 18-24. 1907.

195. Depth of a mulch. — The depth of a mulch is an important question in humid regions. Not only must all the water in the layer be sacrificed in order to make the mulch effective, but the plant-food of that layer is temporarily withdrawn from use. In humid areas, where the surface soil is usually not over eight or ten inches in depth, the latter consideration is vital, since the fertility of the soil would be greatly depressed by a deep soil mulch. Another factor to be considered here is the possible root pruning that may occur while the mulch is being formed. While not of importance early in the season, it is worthy of considerable attention when the intertilled crop attains some age. It has been shown, with such crops as corn, that considerable depression in yield may result from the maintenance of a mulch at too great a depth, some of the feeding roots being cut off thereby. For such reasons the average depth of mulch for humid regions and in dry-farming operations has become regulated to about three inches, although in the late cultivation of corn a less depth than this is advocated. In irrigated regions where little rainfall occurs and where the soil is very deep and uniformly fertile, mulches as deep as ten or twelve inches are sometimes found, especially in orchards. As rainfall occurs but few times during the season, such a mulch often needs no attention except for its original formation. With crops having shallow roots a thinner mulch layer must of course be used.

196. Résumé of mulch control. — To summarize briefly, the cardinal points in mulch control are: (1) mulches are more effective and more easily maintained in an arid than in a humid climate; (2) their efficiency depends directly on their dryness, looseness, and granulation; (3) sandy soil is more easily maintained as a mulch than clay soil;

(4) from two to three inches is ordinarily the most effective depth; (5) after a heavy rain, the soil mulch must be renewed by tillage, and this is much more urgent on clay than on sandy soil; even without rain, a clay mulch may become inefficient; (6) tillage for mulch purposes must ordinarily be more frequent in spring or during periods of heavy rain, than at other times of the year; (7) the use of foreign materials as mulches may be justified under special circumstances.

197. **Water saved by a mulch.** — It is very difficult to quote data regarding the capacity of a mulch to conserve moisture, since conditions vary to such a degree from one region to another. Again, water may not be the limiting factor in crop growth, and even if moisture were saved there might be but little influence on crop yields. As a general rule, mulches are most easily maintained and most effective in arid and semiarid regions. Since there is no doubt that moisture, under such conditions, is the limiting factor in plant growth, data from such regions should be especially significant.

MOISTURE CONTENT OF MULCHED AND UNMULCHED EASTERN MONTANA SOILS. AVERAGE OF THREE YEARS.[1] OCTOBER 6

	MULCHED	UNMULCHED
First foot	16.8	10.8
Second foot	16.4	9.4
Third foot	13.2	9.5
Fourth foot	10.1	8.8
Fifth foot	9.6	8.5
Average	13.2	9.4

[1] Buckman, H. O. Moisture and Nitrates in Dry Land Agriculture. Proc. Amer. Soc. Agron., Vol. 2, p. 121. 1910.

If the wilting point of this soil is 8 per cent, the mulched area contains more than twice as much available moisture. This 3.8 per cent of available moisture by which the mulched soil excels the unmulched is equivalent in a five-foot depth to about 260 tons of water, enough to increase the crop by a ton of dry matter — certainly not an insignificant saving where crop yield and moisture are so very closely correlated.

A considerable amount of experimentation[1] is available which seems to indicate that mulching a soil does not increase its yield over a soil not so treated. One reason for this, as already suggested, may be in the fact that water may not have been the limiting factor, the rainfall having been just right in amount and distribution. Again, the roots may have so intercepted the capillary water as to have allowed no more evaporation from the unmulched soil than from the mulched. In some soils hard layers often form which act in repelling capillary movement. Such a condition would function as successfully in checking losses as if a true mulch were present. In the study of mulches and their value in increasing a crop, decided opinions should not be advanced until every phase has been thoroughly investigated regarding the exact factors dominant in the determination of yield. The extended use of soil mulches in the Corn-Belt and in dry-farming operations argues for their benefits.

198. Effect of mulches other than on moisture. — That mulching a soil has other effects besides the conserving of moisture is universally evident. In general the physical condition of the soil is always better after a crop that has

[1] Cates, J. S., and Cox, H. R. The Weed Factor in the Cultivation of Corn. U. S. D. A., Bur. Plant Indus., Bul. 257. 1912.

been intertilled. Not only has the surface been kept well granulated, but the presence of optimum moisture below has allowed the granulating agents to become more active. The following of potatoes by corn is, at least partially, an attempt to take advantage of the better tilth of the soil with a crop that is particularly benefited thereby. Again, a mulch not only tends to allow a ready entrance of water into the soil, but at the same time increases the water-holding capacity — factors already emphasized in the discussion of control of losses by percolation and run-off. By keeping down weeds[1] another saving is effected, not only in moisture but also in plant-food. Some results from an experiment[2] conducted at Cornell University serve to illustrate the relation of mulches and weeds to soil moisture and crop production in a humid region in a season of good rainfall. The crop grown was maize. Every third plot was a check and was given normal treatment: —

	Yields Calculated to Basis of 100 on Check Plots	Soil Moisture August Per Cent
Check plot	100	21.1
Weeds removed, but not cultivated	96	18.2
Mulched with straw	121	25.0
Check plot	100	18.2
No cultivation; weeds allowed to grow	31	9.8
Usual cultivation; weeds allowed to grow	98	17.0
Check plot	100	17.2

[1] Cates, J. S., and Cox, H. R. The Weed Factor in the Cultivation of Corn. U. S. D. A., Bur. Plant Indus., Bul. 257. 1912.

[2] Craig, C. E. The Cause of Injury to Maize by Weeds. Presented as a thesis for the degree of M. S. A., Cornell University. Unpublished. June, 1908.

The application of a soil mulch is not confined to intertilled crops such as maize, potatoes, vineyards, fallow, and the like. Under some conditions it may be applied to grain fields with good results. In those sections of the country where dry farming is practiced, it is not uncommon to drag the grainfield with a sharp-tooth harrow, the teeth pointing backward. This is begun when the plants are small, and may be continued until they attain a considerable size or until they sufficiently shade the ground to greatly reduce surface evaporation.

198. **General usefulness of a mulch.** — While a soil mulch is used primarily in order to conserve moisture, its relationships are different in different regions according to climatic and cropping peculiarities. In dry-farming regions a mulch is maintained as nearly as possible the year round, since moisture must be carried from the previous summer and winter to the growing season in order to supplement the rainfall occurring at that time. In irrigated regions a mulch is useful in two ways — by conserving the rainfall and by checking the loss of irrigation water; after the latter is once in the soil less additional water need be applied and the consequent cost of irrigation is much less. Again, in arid regions where there is an excess of soluble salts, rapid evaporation is detrimental since these salts tend to concentrate near the surface and become harmful to plants. The prevention of the rise of alkali is therefore a very important function of the soil mulch in such regions.

In humid regions the utilization of a soil mulch is much less intense, since the conservation of moisture over long periods is unnecessary, due to the rainfall. However, during the growing season periods of drought occur, when if available water is lacking in the soil, the

crop suffers. The amount of moisture conserved by a mulch will usually keep the plant growing normally through such periods, while crops on soils not so treated may suffer greatly. The tiding of crops over short periods of light rainfall is the chief function of mulches in humid climates.

200. Other practices affecting evaporation losses.—Although the control of water by mulches is such an important consideration, other means of checking losses are available. These may be grouped under five heads: (1) fall and early spring plowing, (2) rolling, (3) shelters, (4) level cultivation, (5) plants.

201. Fall and early spring plowing. Fall and early spring plowing owe much of their efficiency to the conservation of moisture effected through the creation of a mulch over the surface. Fall plowing may be practiced for a number of reasons, but in regions of deficient rainfall, particularly in winter, the conservation of the moisture in the soil at the close of the growing season is an important consideration. This practice is well adapted to those soils in semiarid sections that do not blow too badly when fall-plowed, and where the winter rain is not sufficient to saturate the soil. If the soil is left in the bare, hard condition resulting from the removal of a crop of maize, wheat, or barley, a large quantity of water may be lost by evaporation during the fall months.

For the average farmer in humid regions where the winter rainfall is sufficient to saturate the soil, early spring plowing, coupled with tillage, is very important. Not only may moisture be conserved, but the soil is worked at the stage when it yields most readily to pulverization. Fallow land, and bare stubble land of fine-textured soil, are most benefited, since they become

compact to the very surface as a result of the winter rain and snow, and are therefore in condition for the most rapid loss of water. They should be plowed as early as practicable without injury to their structure. At the Wisconsin Experiment Station[1] two adjacent pieces of land very uniform in character were plowed seven days apart. At the time when the second plot was plowed, it was found to have lost 1.75 inches of water from the surface four feet in the previous seven days, while the piece plowed earlier had actually gained, doubtless by increased capillarity, a slight amount of water over what it had contained when plowed. There was a conservation of nearly two inches of water in the root zone as a result of plowing one week earlier — enough to produce 1500 pounds of dry matter in maize to the acre, if properly utilized.

202. **Rolling.** — Very often in the spring, when the seed bed is very loose, rolling is resorted to, in order to bring about a compaction of the soil. At the same time capillarity is established with the firmer earth beneath, and as the moisture moves upward a rapid germination of the seed is induced. Care must be taken that this capillarity be checked once it has performed this office, as great losses from evaporation may occur at the surface and the crop be robbed of much available water. It is an economic procedure in such cases to follow the roller after a few days with a harrow, in order that a mulch may be established and this loss checked.

203. **Shelters.** — Shelters of any kind, whether natural or artificial, tend to break the wind velocity and thereby check losses by evaporation. Strips of timber are com-

[1] King, F. H., The Soil, p. 189. New York. 1906.

monly grown or retained for this purpose. Wooden fences and walls of one sort or another have a similar effect. Windbreaks composed of growing plants have the disadvantage that for a considerable distance beyond the spread of their branches their roots penetrate the soil and use the moisture, which is one reason for the smaller growth of crops near trees. Bearing on the efficiency of windbreaks, results by King[1] show that when the rate of evaporation at twenty, forty, and sixty feet to the leeward of a black oak grove fifteen to twenty feet high was 11.5, 11.6, and 11.9 cubic centimeters, respectively, from a wet surface of twenty-seven square inches, the evaporation was 14.5, 14.2, and 14.7 cubic centimeters, at two hundred and eighty, three hundred, and three hundred and twenty feet distant — or 24 per cent greater at the *outer* stations than at the inner ones. A scanty hedgerow reduced evaporation 30 per cent at twenty feet and 7 per cent at one hundred and fifty feet, below the evaporation at three hundred feet from the hedge.

Very often tent shelters are used in the growing of tobacco. The commonest form of the tent is a frame eight or nine feet high, over which is spread a loosely woven cloth. Investigations by Stewart[2] in Connecticut showed: (1) That the tent greatly reduced the velocity of the wind. This reduction amounted to 90 per cent when the outside velocity was seven miles an hour, and 84 per cent when the outside velocity was twenty miles an hour, there being a small regular decrease in relative efficiency with increased velocity of the wind. (2) The relative humidity under the tent was higher than outside,

[1] King, F. H. The Soil, p. 205. New York. 1906.

[2] Stewart, J. B. Effects of Shading on Soil Conditions. U. S. D. A., Bur. Soils, Bul. 39. 1907.

and during a good part of the time attained a difference of 10 per cent. The effect of this was to reduce evaporation by from 53 to 63 per cent on different days in July, in spite of a higher temperature inside the tent. (3) The direct effect of this was to increase the moisture content in the soil in spite of a larger crop growth under the tent. These differences are shown by the following curves (see Fig. 45), which represent the percentage of water in the soil to a depth of nine inches from June 13 to August 1.

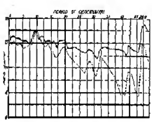

FIG. 45. — Curves showing the percentage of moisture in a sandy soil to the depth of nine inches inside and outside of a loosely woven tent over a period of about fifty days. Heavy line, moisture inside of tent; broken line, moisture curve of soil outside of tent.

Not only was the tent effective in preventing evaporation and thereby increasing the average moisture content of the soil, but the soil was able to maintain a more uniform content, due to the freer movement and adjustment of the capillary water under the tent — conditions more conducive to rapid crop growth.

204. Level cultivation. — The velocity of the wind next to the ground may be checked by ridging the soil. It is doubtful whether this practice conserves moisture,

because a greater amount of surface is exposed over which evaporation may take place. On the other hand, wide experience, as well as investigation, indicates that, for the conservation of water, level culture is better than ridged culture. This principle has led to the gradual abandonment of the practice of "laying by" corn and potatoes with a high ridge. In all regions of deficient rainfall, the best practice prescribes level tillage and a fine, dry mulch, both of which are attained by the frequent use of shallow-running small-tooth cultivators. Many experiments have demonstrated the larger crop yields to be obtained, on the average, from this practice.

205. **Plants.** — Plants growing on the soil tend to check evaporation from two causes — (1) their shading effects, and (2) the tendency of the roots to intercept capillary water as it moves upward and to appropriate it for plant growth. Plants, however, tend to intercept a certain amount of rain and prevent its ever reaching the soil. The amount of water wasted in this way by forests ranges from 15 to 30 per cent. In general this tendency just about offsets the saving that occurs from shading.

206. **Summary of moisture control.** — It is clearly seen from the discussion of moisture control that the structural condition of the soil is the secret of successful operation. Run-off and leaching are reduced by increased capillary capacity, a structural relationship. Evaporation is checked by a soil mulch, which depends for its effectiveness on its physical condition. Drainage, lime, addition of organic matter, and tillage in perfecting granulation function in increasing the ease and effectiveness with which soil moisture may be controlled. It must be clearly kept in mind that all such control is directed

toward the regulation of the soil moisture in such a way that an optimum water supply may be held constantly in the soil during the growing season. If this can be accomplished, the largest crop yields may be expected that are possible under the existing fertility conditions of any soil.

CHAPTER XIV

SOIL HEAT[1]

Normal plant growth is practically suspended below a temperature of about 40° F., while proper germination of seeds does not proceed much below that temperature. As a rule it is not desirable to place either seeds or plants in a soil in which active growth does not take place almost immediately, since certain molds and fungi, active at low temperature, may sap their vitality and ultimately cause their destruction. The desirable chemical reactions in the soil are checked to a certain extent by lack of heat, while the important biological activities are greatly impeded, if not brought entirely to a standstill, when the soil temperature approaches 32° F. Such functions as the decay and putrefaction of organic matter, the formation of ammonia from simple humic bodies, the building-up of this ammonia into the nitrate form, and the fixation of the free nitrogen either by free-fixing or symbiotic bacteria, depend on an optimum soil temperature.

A knowledge of the functions of heat, therefore, especially as to its relationship to plant growth and bacterial activities, becomes important; for the farmer can to a certain extent control soil temperature. He is able

[1] For bibliography of the literature of soil heat, see Bouyoucos, G. J. An Investigation of Soil Temperature and Some of the Most Important Factors Influencing It. Michigan Agr. Exp. Sta., Technical Bul. 17, pp. 194–196. 1913.

also to govern the time when his sowing and planting are performed in such a way that the soil will be fitted, at least as far as heat is concerned, for proper seed germination and plant growth.

207. Relation of heat to germination and growth. In order to show the exact relationship of heat to germination of seeds and to the growth of plants, the following data from Haberlandt[1] are given. While these tables are not exact, they show clearly the necessity of careful control of temperature in the propagation of plants:—

THE RELATION OF TEMPERATURE TO THE GERMINATION OF CERTAIN SEEDS (IN DEGREES FAHRENHEIT)

	MINIMUM	OPTIMUM	MAXIMUM
Corn	49	93	115
Scarlet bean	49	93	115
Pumpkin	52	93	115
Wheat	41	84	108
Barley	41	84	99

THE RELATION OF TEMPERATURE TO THE GROWTH OF CERTAIN PLANTS (IN DEGREES FAHRENHEIT)

	MINIMUM	OPTIMUM	MAXIMUM
Wheat	32–40	77–88	88–95
Barley	32–40	77–88	88–98
Corn	40–51	88–98	98–111
Peas	32–40	77–88	88–98
Buckwheat	37–40	77–88	98–111
Melon	60–65	88–98	111–122
Pumpkin	51–60	98–111	111–122

[1] Haberlandt, F. Die Oberen und Unteren Temperaturgrenzen für die Keimung der Wichtigeren Landwirthschaftlichen Samenarten. Landw. Versuchs. Stat., Band 17, Seite 104–116, 1874.

It is noticeable that there are here three groups of plants as far as temperature conditions for optimum growth are concerned. Wheat represents the crops that germinate and grow at a relatively low temperature. Corn requires a medium high temperature for proper growth, while melons and pumpkins represent crops the temperature requirements of which are very high. These needs must be supplied for a proper development of such plants, and must of course be considered in crop adaptation as well as in soil management in general.

208. Chemical and physical changes due to heat. — In the soil a certain amount of chemical action is going on, no matter what the temperature may be; but it is without doubt true that this activity is greatly accelerated by an increase in soil heat. This arises from two causes: (1) because heat increases the solubility of the soil constituents; and (2) because the activity of the soil organisms is stimulated to such an extent as to in turn influence chemical reaction. The increased production of carbon dioxide is a good example of this relationship. The warming of the soil in spring and summer, therefore, by stimulating the amount of solution, increases to a marked extent the constituents available for plant growth.

The effect of temperature is less marked in a direct way on the structure of the soil than on its chemical or biological nature unless the freezing point is reached. At this point, if moisture is present, the soil mass is disrupted and may become rather granulated if the freezing process is often repeated. The practice of fall-plowing in order to better the tilth of the soil is really taking advantage of this natural phenomenon. A change in temperature also causes the expansion or contraction of the

soil gases and may greatly facilitate their movement. This is essentially a physical relationship. It must be kept in mind, however, that with heat as with other soil factors, no clear-cut and distinct discussion of its effects in one direction may be made without considering the indirect influences that are continually opening up avenues which lead to phases more or less foreign to the one under discussion. This serves to emphasize the close correlation of the various factors and conditions that must be dealt with in a study of soils.

209. Sources of soil heat. — The soil may receive heat directly or indirectly from three general sources: (1) from the sun, (2) from the stars, and (3) by conduction from the heated interior of the earth. The two last-named sources are so unimportant as to warrant no further discussion, since the amount of heat received by the soil therefrom is so small as to be negligible.

The sun, then, either directly or indirectly supplies all the heat and energy that make it possible for soils to support vegetation. This heat is derived in various ways, as follows: —

(1) By direct radiation of rays, both of light and of invisible heat. These rays when absorbed tend to raise the temperature of the absorbing medium. This source of heat is by far the most important and may be designated as the direct method of heat induction.

(2) A considerable amount of heat may be derived by radiation and conduction from the atmosphere surrounding the earth. This heat has of course been originally obtained from the sun and is passed on to the soil, the length of the waves being somewhat changed in the transition. Clouds may sometimes serve as a blanket and shut

in accord the earth heat that would otherwise be entirely lost so far as the soil is concerned.

(3) A certain amount of heat may be brought to the soil by precipitation. A warm spring rain, by falling on the earth and percolating into its subsoil, may be a determining factor in crop growth. Although the aggregate amount of heat added in this way is small, the opportuneness of its application is of no small importance. A warm rain often imparts an impetus to plant growth which may be noticeable for many weeks afterward.

(4) A large amount of heat is annually entrapped by growing plants. This energy is stored up and may ultimately be liberated by the decay of the tissue. If such oxidation takes place in the soil, as it very largely should under good farm management, a certain amount of heat is liberated in the soil. How important this is it is difficult to say, for such energy is given off so gradually as to be rendered difficult of measurement. Bacterial activity is very closely allied to the utilization of such heat. Except under exceptional conditions, as in hotbeds or very heavily manured lands, such heat has no appreciable effect in altering the temperature of a normal soil.

210. **Factors affecting soil temperature.** The temperature that the soil of any given locality may attain is dependent on a certain group of factors so closely related as to make their separate consideration sometimes rather difficult. For convenience these factors may be listed as follows, the actual temperatures and their probable fluctuations under field conditions being reserved until the various intrinsic and external factors of soil heat have been discussed: —

1. Specific heat.
2. Absorption
3. Radiation
4. Conductivity and convection
5. Evaporation of moisture
6. Organic decay
7. Slope
8. Heat supply and its effects

211. Specific heat. The specific heat of any material may be defined as its thermal capacity as compared with that of water. It is the ratio of the quantity of heat required to raise the temperature of a given weight of the substance one degree Centigrade to the quantity needed to change an equal weight of water from 19.5° to 20.5° Centigrade. A knowledge of the specific heat of soil is important because of the general light it sheds on the warming-up of a soil in spring and on its rate of cooling in autumn. The data from a number of investigations, in the order of their priority, as here quoted, the calculations being based on dry soil: —

WEIGHT SPECIFIC HEAT OF SOILS

Pfaundler[1] (1866)		Liebenberg[2] (1878)	
Fine sand	.1923	Coarse sand . . .	.1920
Alluvial soil . . .	.2507	Diluvial loam .	.2250
Granite soil . . .	.3480	Fine loam	.2770
Humous soil . . .	.4143	Humous loam .	.3290
Peat.	.5069	Granite soil . . .	.3880

[1] Pfaundler, L. Ueber die Wärme Capacität Verschiedener Bodenarten und deren Einfluss auf die Pflanze. Ann. d. Physik u. Chemie, Band 205, Seite 102–135. Leipzig, 1866.

[2] Liebenberg, R. von. See Lang, C. Ueber Wärme Capacität der Bodenconstituenten. Forsch. a. d. Gebiete d. Agri-Physik, Band I, Seite 118. 1878.

Lang[1] (1878)		Patten[2] (1909)	
Coarse sand	.1960	Norfolk sand	.1848
Limestone soil	.2490	Podunk fine sandy loam	.1828
Humous soil	.2570	Hagerstown loam	.1914
Garden soil	.3670	Leonardtown loam	.1944
Peat	.4770	Galveston clay	.2097

Bouyoucos[3] (1913)	
Sand	.1929
Gravel	.2045
Clay	.2059
Loam	.2154
Peat	.2525

212. Variations of specific heat. — These figures show a considerable amount of variation, part of which is of course due (1) to inaccuracies in the designation of the materials used, (2) to differences in methods, and (3) to differences in technique. Allowing for these probable errors, there still seem to be other factors involved. One of these might be texture, since, according to the earlier investigators, the finer mineral soils seem to possess a higher specific heat. The data of Bouyoucos and Patten, however, seem to controvert this assumption. An investigation more to the point is that of Ulrich.[4] In work-

[1] Lang, C. Ueber Wärme Capacität der Bodenconstituenten. Forsch. a. d. Gebiete d. Agri.-Physik, Band I, Seite 109–147. 1878.

[2] Patten, H. E. Heat Transference in Soils. U. S. D. A., Bur. Soils, Bul. 59, p. 34. 1909.

[3] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 13. 1913.

[4] Ulrich, R. Untersuchungen über die Wärmekapacität der Bodenkonstituenten. Forsch. a. d. Geb. d. Agri.-Physik, Band 17, Seite 1–31. 1894.

ing with various grades of quartz sand he obtained practically identical specific heats with the various separates:—

SPECIFIC HEAT OF VARIOUS GRADES OF SAND AS FOUND BY ULRICH

Diameter of Sands in Millimeters	Specific Heat
2–1	.1912
1–.5	.1908
.5–.25	.1922
.25–.171	.1919
.171–.114	.1910
.114–.071	.1904
.071–.010	.1890

It is evident, therefore, not only that texture has no very great direct effect on specific heat, but also that the controlling factor in the data already quoted is the composition of the soil. The predominate minerals found in soils possess a specific heat of from .180 to .220.[1] This rather narrow range would normally be still further lessened, since an average soil is a complex of the different minerals. Humus, then, possessing a specific heat of about .5 must, when added to any soil, increase markedly its thermal capacity and would undoubtedly be the determining factor in weight specific heat of the mixture.

213. Specific heat based on volume of soil.— Under normal conditions, however, the soil contains a considerable amount of pore space, and different soils would

[1] Ulrich, R. Untersuchungen über die Wärmekapazität der Bodenkonstituenten. Forsch. a. d. Geb. d. Agri. Physik, Band 17, Seite 1–31. 1894.

therefore show different weights to the cubic foot. A specific heat comparison based on weight, therefore, does not yield a fair idea of the heat capacities of two soils. The multiplication of the weight specific heat by the apparent specific gravity of the soil in question will obviously yield a volume specific heat, which is a much more rational basis for comparison. A quotation from Ulrich[1] makes clear the value of such a computation:

SPECIFIC HEAT OF SOIL EXPRESSED BY WEIGHT AND BY VOLUME OF SOIL

	APPARENT SPECIFIC GRAVITY	SPECIFIC HEAT BY WEIGHT	SPECIFIC HEAT BY VOLUME
Sand	1.52	.1909	.2901
Clay	1.04	.2243	.2333
Humus	.37	.4431	.1639

It is evident that in the first case the specific heat is governed by the organic content of the soils in question; the greater the amount of organic material present, the higher is the thermal capacity. Such is not the case when the specific heat of the soil is calculated on a volume basis. In an expression of the thermal capacity on this rational basis, namely, that of volume, the apparent specific gravity, or volume weight, is the dominant factor. The addition of humus when this method of expression is employed merely serves to lower the volume weight, and

[1] Ulrich, R. Untersuchungen über die Wärmekapazität der Bodenkonstituenten. Forsch. a. d. Geb. d. Agri.-Physik, Band 17, Seite 1-31. 1894.

a reduction of specific heat thereby occurs. Under such conditions more heat is necessary to raise the temperature of the sand than is the case with the weight expression. This is because of its high apparent specific gravity. The clay shows very little change, as its apparent specific gravity is about one; but the humus exhibits a marked falling-off, due to its exceedingly low volume weight. The factor that tends to vary the specific heat of dry soil under natural conditions, therefore, is the apparent specific gravity, or the volume weight. By deep and efficient plowing the farmer may encourage the warming of his soil, due to a lowered thermal capacity. By increasing its humus content he may attain the same result, since the volume weight is depressed to a markedly greater extent than the specific heat is increased by the addition of organic matter. In fact, any operation on or any addition to the soil that will vary its apparent specific gravity will in turn affect the specific heat.

214. Effect of water on specific heat. — One other factor, much more potent than the two already mentioned, is yet to be discussed. This factor is water, so universally present in soils and of the greatest importance in all natural soil phenomena. As the specific heat of water is very high compared with the thermal capacity of the soil constituents, any addition of it must naturally raise the specific heat of a normal soil. That moisture, not apparent specific gravity nor organic content, is the controlling factor is demonstrated from the following data, calculated by Ulrich[1] on a volume basis: —

[1] Ulrich, R. Untersuchungen über die Wärmekapazität der Bodenkonstituenten. Forsch. a. d. Geb. d. Agri.-Physik, Band 17, Seite 27. 1894.

THE EFFECT OF SOIL MOISTURE ON THE VOLUME SPECIFIC HEAT OF SOIL, THE MOISTURE BEING EXPRESSED AS A PERCENTAGE OF THE TOTAL WATER CAPACITY

	Dry Soil	10 Per Cent of Water	20 Per Cent of Water	30 Per Cent of Water	40 Per Cent of Water	50 Per Cent of Water	60 Per Cent of Water	70 Per Cent of Water	80 Per Cent of Water	90 Per Cent of Water	100 Per Cent of Water
Quartz	.1440	.1700	.2883	.3058	.4416	.4950	.5048	.5599	.5975	.7068	.8553
Kaolin	.2330	.3045	.3538	.4170	.4702	.5036	.6002	.6620	.7331	.7612	.8608
Humus	.1567	.2630	.2907	.3087	.4762	.5448	.6028	.7006	.7607	.8600	.9449

It is at once evident, from these data and the accompanying curves (see Fig. 46), that moisture, in its effect on the specific heat of an average soil, is so potent as to

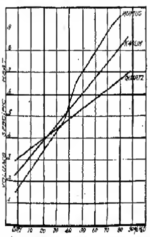

FIG. 46.—Curves showing the effect of moisture on the volume specific heat of soils of different texture and humus content.

entirely obscure in most cases the variations due directly to such factors as apparent specific gravity and humus content. Organic matter, because of its high water capacity, usually accentuates the dominance of moisture in this respect. While a humous soil of low volume weight may warm up most easily when dry, its high water content may so increase its thermal capacity as to markedly retard its temperature changes. This is exemplified by Petit[1] and Bouyoucos[2] in their study of frost penetration in peat. This soil was the last to freeze in winter and, conversely, the last to thaw in spring. The advantage of removing excess water by drainage is of importance from this standpoint, as a wet soil is necessarily a colder soil in spring than one that is well drained. This at least partially accounts for the fact that a sandy soil is usually an early one, and is therefore of particular value in trucking operations.

215. Absorptive power of soils for heat. — The greater proportion of the heat received by the soil is obtained by direct radiation from the sun. This radiant heat is propelled by free wave action in the ether, the space intervening between the sun and the earth being but little affected by the transfer. Were the total amount of heat received from a vertical sun by any unit surface wholly absorbed by a layer of soil twelve inches thick, the temperature of the soil would rise thirty degrees Fahrenheit an hour. Such is not the case under normal

[1] Petit, A. Untersuchungen über den Einfluss des Frostes auf die Temperaturverhältnisse der Böden von Verschiedener Physikalischer Beschaffenheit. Forsch. a. d. Geb. d. Agri-Physik, Band 18, Seite 285–310. 1893.

[2] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 214. 1913.

conditions, however, as the atmosphere continuously refracts, reflects, and absorbs a certain amount of this radiant energy. More important still are certain inherent qualities of the soil itself which function materially in the modification of the amount of heat absorbed. These intrinsic factors are color, reflection, texture, and structure.

216. **Effect of color on absorption of heat.** (See Fig. 47.) — In a natural soil it is very difficult to effect a change in soil color without changing the texture, structure, and more particularly the constitution, of the particles. In order to eliminate these disturbing factors in a study of heat, a quartz sand colored with various dyes was used by Bouyoucos.[1] The following data, taken at Lansing, Michigan, on a clear, warm day in August, illustrate the general effects of color on absorption: —

Effect of Different Colors on Heat Absorption by Quartz Sand, August 5, 1.30 p.m.

Color	Temperature (Degrees Centigrade)
Black	37.6
Blue	36.7
Red	35.0
Green	34.7
Yellow	32.6
White	31.7

It is quite evident that the darker the soil, the greater is its absorptive power. This is because of differences in reflection, a light-colored soil reflecting more of the heat rays than one of a darker color. There might be a question here as to the difference in radiation arising from

[1] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 31. 1913.

color, the white soils radiating more heat than the black ones. The following data from Bouyoucos,[1] substantiating those of Lang,[2] are a conclusive negative answer to such a query:—

RADIATION OF DIFFERENT-COLORED SANDS, WHITE BEING TAKEN AS 1.00

White	1.000
Black	.991
Blue	.981
Green	.981
Red	.991
Yellow	.989

The addition of organic matter, provided its decay has been of the proper sort, will consequently always raise the soil temperature, other factors of course being equal. Wollny,[3] in experimentation with soils covered with thin layers of different-colored material, found marked differences under field conditions. The black soil not only exhibited the highest temperature, but also showed a greater amount of fluctuation. The minimum temperatures of the different-colored soils were almost the same. The temperature differences of course decreased with depth. Some typical data obtained on a clear day, as quoted from Wollny's work, are as follows:—

[1] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 30. 1913.

[2] Lang, C. Über Wärme-absorption und Emission des Bodens. Forsch. a. d. Gebiete d. Agri.-Physik, Band I, Seite 379–407. 1878.

[3] Wollny, E. Untersuchungen über den Einfluss der Farbe des Bodens auf dessen Erwärmung. Forsch. a. d. Geb. d. Agri.-Physik, Band I, Seite 43–69. 1878. Also, Untersuchungen über den Einfluss der Farbe des Bodens auf dessen Erwärmung. Forsch. a. d. Geb. d. Agri.-Physik, Band IV, Seite 327–365. 1880.

Temperatures of Differently-colored Soils at a Depth of 4 inches, taken June 23, 1878, at Munich (in Degrees Centigrade)

Time	Air	Black	White
Midnight	9.8	13.8	13.8
2 a.m.	10.0	12.4	12.4
4	7.6	10.7	10.8
6	16.0	9.8	9.8
8	19.8	10.4	10.9
10	23.0	15.7	13.8
Noon	25.9	22.1	17.6
2 p.m.	25.4	26.8	23.2
4	24.6	29.4	23.6
6	22.6	28.8	24.0
8	18.4	27.2	23.6
10	16.0	24.0	21.6

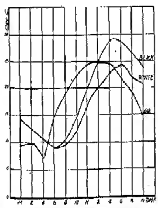

Fig. 47.—Curves showing the temperature variation of different-colored soils at a four inch depth compared with air temperature. Munich, June 23, 1878.

Besides the quite obvious effect of the dark color on the rate of heat absorption, two other points are worthy of notice. The first is the tendency of the soil temperature to lag behind the temperature of the air, and the second is the almost equal minimum reached by the two soils. The latter point would seem to indicate also that color had little differential effect on the heat lost from the soil by radiation into the air.

217. Effects of texture and structure on heat absorption.—Ordinarily the texture and the structure of a soil, other conditions being equal, have little direct influence on rate of absorption. Wollny[1] found with dry and moist soil that the coarser the particles, the higher is the temperature during warm weather. A loose, open structure was always more favorable for high temperatures than one more finely pulverized. Wollny's temperature differences, however, were very small, and it is probable that the experimental error, particularly due to lack of moisture control, was greater than the observed differences. Under normal conditions the practical effects arising from the influence of texture and structure on rate of absorption are probably entirely eliminated by other factors. The importance of texture and structure, as will be shown later, is in the direction of the control of soil heat through their influence on soil moisture. Moisture in turn is a potent factor in the ultimate soil temperature, as it influences specific heat, radiation, and evaporation to such an extent.

218. Radiation of heat by soil.—The principal loss

[1] Wollny, E. Untersuchungen über den Einfluss der Struktur des Bodens auf dessen Feuchtigkeits- und Temperaturverhältnisse. Forsch. a. d. Geb. d. Agri.-Physik, Band V, Seite 145–[illegible]. 1882.

of heat by the soil is through radiation, this radiation being controlled by certain factors of which moisture content, soil mulches, artificial coverings, shelters, and clouds are the most important. Color as a factor in radiation has already been eliminated by the work of Bouyoucos and Lang. The effects of texture and structure have also been investigated by these authors, as well as by other physicists. The general results seem to indicate that unless a dry soil is dealt with these factors may be eliminated from consideration as far as their direct practical effect on radiation is concerned. Of course, indirectly through their influence on such factors as moisture, they are of extreme importance.

An increase in the moisture of a soil has the general effect of heightening the radiation ratio. This, together with the effects of evaporation and of increased specific heat, accounts for the fact that an undrained soil in spring is a cold soil. Bouyoucos[1] found the following relationships between moist and dry soils:—

EFFECT OF MOISTURE ON RADIATION

Soil	Percentage of Moisture	Radiation of Moist Soil	Radiation of Dry Soil
Gravel	4.7	100	92.4
Sand	6.3	100	93.1
Clay	17.3	100	91.9
Loam	25.8	100	90.9
Peat	84.9	100	86.1

Mulches, either natural or artificial, tend to check the loss of soil heat through their covering effect and their

[1] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 34. 1913.

influence on radiation. As a mulch is usually dry, its radiant power is lower than that of the moist soil beneath. Shelters decrease radiation by checking air movement. The vegetation growing on soil also lowers radiation through its covering effect, although the temperature of soils covered with vegetation is usually low in summer due to the obstruction of the sun's rays. Clouds, by shutting in the heat, tend to check radiation and in many cases prevent a frost that would otherwise occur. The protecting effect of snow is well illustrated from the following data, taken from Boussingault: —

EFFECT OF SNOW ON SOIL TEMPERATURE.[1] (TEMPERATURE IN DEGREES CENTIGRADE)

DATE AND HOUR	AIR	ON SNOW	UNDER SNOW
Feb. 11, 5 P.M.	+2.5	−1.5	0.0
Feb. 12, 7 A.M.	−3.0	−12.0	−3.5
Feb. 13, 7 A.M.	−3.8	−3.2	−2.0
Feb. 13, 3.30 P.M.	+4.5	1.0	0.0

One of the important features of soil heat radiation is its effect on air temperature. As the radiant energy from the sun passes through the atmosphere, very little of the heat is appropriated, due to the wave lengths. But, as this energy is radiated from the soil, the heat waves have become shortened and are readily taken up by the atmosphere, particularly if the latter is moist. However, as the air is always in motion its heat is not controlled by the soil radiation of any particular locality.

[1] Warington, R. Lectures on Some of the Physical Properties of Soils, p. 159. Oxford. 1900.

In fact, the soil may be warmed by conduction of heat from air to soil. This probably occurs to some extent in spring, when the air is growing warmer, due to low specific heat and its movement. The changes in air temperatures are always more rapid and usually greater in range, due to the factors cited above.

219. Conductivity and convection of heat in soils.—While radiation has to do with the transfer of heat by ether waves, conductivity is a term used in relation to molecular transmission of energy through the body under investigation. It may be defined as the amount of heat in calories that will pass across a cube of unit edge (1 centimeter), in unit time (1 second) under a temperature gradient of 1 degree Centigrade. Convection refers to the transmission of heat by actual apparent and visible movements of matter. It is to these two modes of transfer that we owe the possibility of the soil's warming below a surface that receives most of its heat as radiant energy. It must be remembered that in studying the soil we are dealing with a material made up of mineral and organic compounds and always containing, under normal conditions, a certain quantity of water. Air likewise is always present, which, while a poor conductor of heat, may carry energy by convection. Besides these varying substances, often in loose contact and usually containing air capable of considerable movement, there is bound to occur a certain amount of transfer resistance which is the heat resistance found at the boundary of two substances in contact. The study of heat movement downward through a soil is difficult to analyze, since it is almost impossible to control the factors concerned while varying any one. In a normal soil this heat movement occurs through both the agency of conduction and that of convection, depend-

ing on the texture and structure of the soil and the amount of moisture present.

220. Measurement of conductivity. — Ordinarily the conductivity of a soil is measured by applying a constant source of heat as quickly as possible and measuring the change in temperature by means of thermometers set in the soil at regular intervals. (See Fig. 48.) The soil in question should be homogeneous in composition and of uniform compaction, and should contain a definite moisture content. It should of course be at a temperature equilibrium before the heat is applied. Ordinarily radiation and convection currents are diminished somewhat by inclosing the soil in an insulated compartment. The study of heat movement downward instead of laterally is to be recommended, in order that unnecessary air circulation may be avoided to some extent.

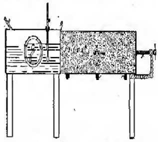

FIG. 48. — Longitudinal section of apparatus for the study of heat conductivity of soil. (C), water at constant temperature; (t), thermometer; (P), copper plates; (F), screw clamp for pressing soil firmly against source of heat; (s), stule for soil box.

221. Effect of texture on conductivity of heat. — The conductivity of a soil is affected by a number of factors

which may or may not lend themselves to modification in the field. From the fact that type is of primary importance in choosing a soil, texture in its relation to conductivity might be considered first. From the work of Wagner[1] and Potts[2] it is clearly established that the coarser the texture of a soil, the faster the rate of conduction of heat will be, other factors remaining constant. Data quoted from the findings of Bouyoucos[3] substantiate these results: —

CONDUCTIVITY OF VARIOUS SOILS AS MEASURED BY THE TIME REQUIRED FOR A THERMOMETER 7 INCHES FROM THE SOURCE OF HEAT TO SHOW A RISE IN TEMPERATURE

Soil	Relative Rate of Conductivity
Sand	1.00
Loam	1.81
Clay	1.77
Peat	4.61

Such results as these are only comparative and qualitative. The difficulties of quantitative determinations are so beset by error that only one investigator has as yet made any consistent attempt along this line. Patten,[4] who has prosecuted such an investigation, finds that such work may be vitiated by thermometer spacing, size of thermometer, error in readings, moisture control, and

[1] Wagner, F. Untersuchungen über das Relative Wärmeleitungsvermögen Verschieden Bodenarten. Forsch. a. d. Geb. d. Agri.-Physik, Band VI, Seite 1–51. 1883.

[2] Potts, E. Untersuchungen Betreffend die Fortpflanzung der Wärme in Boden durch Leitung. Landw. Ver. Stat., Band XX, Seite 273–355. 1877.

[3] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 20. 1913.

[4] Patten, H. E. Heat Transfer in Soils. U. S. D. A., Bur. Soils, Bul. 59. 1909.

the necessity of taking time-temperature curves in the unsteady state. His results, expressed as metric K (the heat conductivity coefficient in C. G. S. units), show the same general comparisons as already presented: —

HEAT CONDUCTIVITY OF DIFFERENT SOILS

Soil	K in C.G.S. units (See Definition of Conductivity)
Coarse quartz	.000017
Leonardtown loam	.000882
Podunk fine sandy loam	.000793
Hagerstown loam	.000699
Galveston clay	.000577
Muck	.000349

222. Effects of humus and structure on conductivity. — A disturbing factor always present when soils are used in the determination of the effect of texture on conductivity, is humus. It is evident, in dry soil at least, that an increase in the organic content of a soil means a lowering in conductivity. Humus, therefore, must be listed as a second factor tending to vary the movement of heat through soils. A third factor is the structural condition of the soil under examination. Wagner[1] has shown in this regard that the more compact a soil, the faster is the conduction of heat. This is probably due to the more intimate contact of the soil grains, and a consequent cutting-down of the insulation factors and diminution of the transfer resistance.

223. Influence of moisture on heat conductivity in soil. — The greatest single factor to be considered in conduc

[1] Wagner, F. Untersuchungen über das Relative Wärmeleitungsvermögen Verschiedener Bodenarten. Forsch. a. d. Geb. d. Agri.-Physik, Band VI, Seite 1-61. 1883.

tivity study, however, is the moisture content of the soil The following curve for quartz powder, taken from Patten's[1] work, illustrates its effect and shows how its influence may heavily override the factors already mentioned.

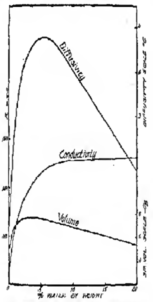

Fig. 40.—Effect of moisture upon the apparent specific volume, heat conductivity, and diffusivity of coarse quartz powder.

[1] Patten, H. E. Heat Transfer in Soils. U. S. D. A., Bur. Soils Bul. 59, p. 30. 1909.

At first glance it appears peculiar that the heat movement through a soil, the mineral constituents of which possess a conductivity coefficient of about .01066, should be raised by the addition of a liquid possessing a value of K of about .00149, a conductivity about one-seventh of the soil minerals. The explanation of this as given by Patten is a lowering of the transfer resistance. He has calculated that heat will pass from soil to water approximately one hundred and fifty times more easily than from soil to air. This being true, it is evident that as the water is increased in any soil and the air decreased, the conductivity coefficient increases. It must be kept in mind, however, that as the moisture increases, the total amount of heat necessary to raise this soil to a given temperature must also be increased. The necessity for the maintenance of a medium moisture content in any soil becomes apparent, although the conductivity may not thereby be at its maximum. The curves in question show that not only is there a change of volume weight, but also there is a decrease in diffusivity with high water percentages — another reason for avoiding excessive moisture contents in a field soil.

As has already been noted, the warming-up of a soil becomes less and less rapid as the subsoil is penetrated. This is not due to lessened conductivity, but rather to a lessened heat supply. Bouyoucos[1] has shown that under natural conditions the tendency of heat is to travel downward more rapidly than laterally, due to a higher moisture in the lower depths of the average field soil. The time-temperature curves and the temperature gradi-

[1] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, p. 25. 1913.

ent for quartz powder as drawn by Patten[1] (see Figs. 50 and 51) illustrate the effect of distance on temperature rise, the conductivity coefficient remaining constant.

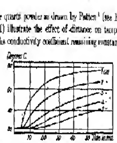

FIG. 50.—Temperature time curves for quartz powder at various distances from the source of heat.

From this brief discussion of conductivity it may be established that such a movement is of importance to plants in carrying heat downward into the soil. While it is affected directly by texture, structure, and humus to a certain extent, moisture is the dominant factor. Under natural conditions it is necessary to maintain a medium moisture content, although the conductivity of heat is not then at its maximum. However, it must always be remembered that convection is active under such conditions and may do much in facilitating heat distribution. Good tilth and increased organic content of any soil, by raising the optimum

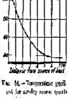

FIG. 51.—Temperature gradient for air-dry coarse quartz powder.

[1] Patten, H. E. Heat Transfer in Soils, U. S. D. A., Bur. Soils, Bul. 59, pp. 23–24. 1909.

moisture content for plant growth, will place the soil in the best possible condition, consistent with plant development, for good heat movement.

224. Effect of evaporation of water on soil temperature. — There is perhaps no factor, besides the loss of heat by direct radiation, which exerts such an effect on soil temperature as does evaporation. The fact that water does not allow the long rays received by direct radiation to pass readily through it accounts for its rapid vaporization. This evaporation, caused by an increased molecular activity, requires a certain expenditure of heat, resulting in a cooling effect on the water and consequently on any material in close contact with it. To evaporate a pound of water requires the withdrawal of about 966 heat units.[1] This is sufficient to lower the temperature of a cubic foot of saturated clay soil about 10° Fahrenheit. The difference in temperature exhibited by wet and dry-bulb thermometers measures the cooling effect of evaporation.

Any condition that increases the rate of evaporation lowers the temperature of the surface concerned. The amount of water present is undoubtedly the controlling factor in this regard. King,[2] found, in his study of a drained and an undrained soil in April, that the former maintained a temperature ranging from 2.5° to 12.5° Fahrenheit higher than the latter. Parks[3] records the same general

[1] An English heat unit is the amount of energy necessary to raise one pound of pure water from 32° to 33° F. It is equal to about 778 foot-pounds.

[2] King, F. H. Physics of Agriculture, p. 220. Published by the author, Madison, Wisconsin. 1910.

[3] Parks, J. On the Influence of Water on the Temperature of Soils. Jour. Roy. Agri. Soc. Eng., Vol. 5, pp. 119-140. 1845.

results in England. Wollny[1] finds a wet soil to be the cooler in the daytime, the difference being roughly proportional to the amount of water present. The effect of the amount of water on the rate of evaporation is of course influenced to a certain extent by texture, structure, and humus, since these factors exert such a marked influence on water capacity and capillary movement.

The practical importance of a study of the effect of evaporation on soil temperature lies in the fact that evaporation can be controlled to a certain extent under field conditions. This is not so true, unfortunately, of radiation and conduction. Thorough underdrainage is the dominant operation in the prevention of cooling by evaporation. By this removal of excess water the specific heat is lowered, radiation is slightly retarded, and convection is facilitated. This means a faster warming of the soil, tending toward an optimum temperature relation as far as the plant is concerned. Optimum moisture encourages optimum heat conditions, as well as other favorable relations whether chemical, physical, or biological. Drainage, lime, humus, and tillage figure in heat control as well as in other phases of soil improvement.

225. Effect of organic decay on soil temperature. — Besides the effect of organic matter on color and its consequent influence on the absorption of heat, it may function in another direction, namely, in producing heat of fermentation. How far this liberation of heat under field

[1] Wollny, E. Untersuchungen über den Einfluss des Wassers auf die Boden. Forsch. a. d. Geb. d. Agri-Physik, Band IV, Seite 147-191. 1881. Also, Untersuchungen über den Einfluss der Oberflächlichen Abtrocknung des Boden auf dessen Temperatur- und Feuchtigkeitsverhältnisse. Forsch. a. d. Geb. d. Agri-Physik, Band III, Seite 325-348. 1880.

conditions is effective in bringing about any important modification of soil temperature it is often difficult to decide. In greenhouses and hotbeds perceptible increases are obtained by the use of large quantities of fresh manure, as high an increase as 75 degrees Centigrade has been observed under such conditions. In the field, however, where the absorption and radiation of heat are very large, where the organic matter makes up only a fraction of the soil's components, and where the applications of barnyard manure are relatively small compared to the bulk of the soil, it is doubtful whether any important increase of soil heat actually occurs. Georgeson,[1] working in Japan with varying quantities of manure, obtained during the first twenty days an excess over the check of only 3.4 degrees Fahrenheit from an application of eighty tons an acre. With twenty tons the increase was 1.7 degrees. Wagner[2] obtained similar results, finding an average excess of 1 degree Fahrenheit from the use of twenty tons of barnyard manure. Bouyoucos[3] has obtained the latest data on this subject. Under controlled laboratory conditions he found that unless excessive amounts of manure were applied no appreciable effects were observed. With an application of ten tons the highest rise was one-half degree Centigrade; after one hundred and three days the manured soil was only one-fourth degree higher than the untreated. Such results show that the heat of fermentation has little important practical influence

[1] Georgeson, C. C. Influence of Manure on Soil Temperature. Agr. Sci., Vol. I, pp. 26–32. 1887.

[2] Wagner, F. Über den Einfluss der Düngung mit Organischen Substanzen auf die Bodentemperatur. Forsch. a. d. Geb. d. Agri.-Physik, Band V, Seite 373–406. 1882.

[3] Bouyoucos, G. J. An Investigation of Soil Temperature. Michigan Agr. Exp. Sta., Tech. Bul. 17, pp. 160–190. 1913.

on soil temperature, so far as the total bulk is concerned. There are without doubt certain localized influences, both chemical and biological, but how important they may be it is rather difficult to say. From what is known at the present time it seems that organic matter exerts its greatest temperature effects through the darkening of the color and the increase in moisture capacity of the soil.

236. Relation of slope to soil temperature. — The relation of exposure to soil heat is the last phase to be considered, with the exception of meteorological factors, which are external in their relationships rather than intrinsic as have been most of the phases already discussed. The slope of a surface varies the amount of heat absorbed from the sun, without affecting, of course, the absorptive power of the surface involved. The greater the inclination of a soil from a right-angle interception of the heat rays, the less rapid will be its rise of temperature in a given unit of time, the source of heat remaining constant. This is because the greater the inclination, the greater is the amount of surface a given amount of heat must serve. It is evident that a less amount of heat will reach each unit of soil surface, and a consequent slower rise in temperature of the soil so situated will result. Under normal conditions, therefore, any inclination that will cause a surface to approach a right-angle interception of the sun's rays will not only increase its rate of temperature rise but at the same time will increase its average seasonal temperature. In the North Temperate Zone this of course is a southerly inclination. The following diagram, illustrating the conditions on the 42d parallel at noon on June 21, makes clear this relationship: —

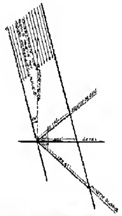

Fig. 58.—Diagram showing the proportional amount of heat received to the unit area by different slopes on June 21, at the 42° parallel north.

It is seen that in this case a southerly slope of 20° receives to a unit area the greatest amount of heat, the level soils and the soils having northerly inclination of 20° differing in the order named. The following table shows the proportional amount of heat received by each one of these soils per unit area at midday with such an inclination of the sun's rays:—

Proportional Amount of Heat Received per Unit Area by Different Slopes on June 21, at the 42° Parallel North Latitude

20° Southerly slope	=	106
Level	=	100
20° Northerly slope	=	81

These figures show not only that the slope itself is important, but also that the direction of the inclination must play a part in the selection of land with its probable temperature relationships borne in mind. The investigations of Wollny,[1] which have since been corroborated by King,[2] and others, may be cited at this point as typical:

Average Temperature at 6 Inches of a Humous Sandy Loam from April to October, 1877, Munich, Germany

	Temperature in Degrees Centigrade
South	14.18
Southeast	14.42
Southwest	14.32
East	13.99
West	13.98
Northwest	13.04
Northeast	13.56
North	12.53

[1] Wollny, E. Untersuchungen über den Einfluss der Exposition auf die Erwärmung des Bodens. Forsch. a. d. Geb. d. Agri.-Physik, Band 1, Seite 263-291, 1878; Untersuchungen über die Feuchtigkeits- und Temperaturverhältnisse des Bodens bei Verschiedener Neigung des Terrains gegen den Horizont. Forsch. a. d. Geb. d. Agri.-Physik, Band IX, Seite 1-70, 1886; Untersuchungen über die Feuchtigkeits- und Temperaturverhältnisse des Bodens bei Verschiedener Neigung des Terrains gegen die Himmelsrichtung und gegen den Horizont. Forsch. a. d. Geb. d. Agri.-Physik, Band X, Seite 1-54, 1887; Untersuchungen über die Temperaturverhältnisse des Bodens bei Verschiedener Neigung des Terrains gegen die Himmelsrichtung und gegen den Horizont. Forsch. a. d. Geb. d. Agri.-Physik, Band X, Seite 345-386. 1887.

[2] King, F. H. Physics of Agriculture, p. 218. Published by the author, Madison, Wisconsin. 1910.

Wollny found also that the soil temperature on the southward slopes varied according to the time of year. For example, the southeasterly inclination was highest in the early season, the southerly slope during mid-season, and the southwesterly slope during the fall. A southeasterly slope is usually preferred by gardeners. Orchardists also pay strict attention to aspect, as it often is a factor in susceptibility to sun scald and other diseases.

King, in comparing a red clay with a southerly slope of 18° to that on a level on July 21, obtained the following results:

Temperature in Degrees Fahrenheit of Red Clay as Influenced by Slope

	First Foot	Second Foot	Third Foot
Southerly slope	70.3	68.1	66.4
Level	67.2	65.4	63.6
	3.1	2.7	2.8

It is apparent immediately that the influence of slope is not confined to the surface, but, owing to conduction and convection, is felt to a considerable depth. Slope, therefore, together with moisture control, becomes a dominant factor in the heat relations of a soil. This is particularly true with specialized crops, with which the early warming of the soil is important. A normally early soil may become late because of exposure, or a naturally late soil may become earlier due to an inclination southward. Slope many times is a dominant factor in the adaptation of crop to soil.

227. Heat supply and its effects.—The direct heat supply is without doubt the controlling factor in soil

temperature, influenced, of course, by the conditions already discussed. The effect of this heat supply is reflected in the seasonal, monthly, and daily soil temperatures at the surface and at varying depths below. The following data illustrate the differences that may ordinarily be expected to take place from season to season on an average soil:—

Average Temperature Readings Taken at Breslau, Germany.[1] Averages of Ten Years, 1901–1910 (in Degrees Fahrenheit)

	Air	1 Inch Deep	8 Inches Deep	16 Inches Deep	28 Inches Deep	40 Inches Deep	52 Inches Deep
Winter . . .	29.4	28.2	33.3	34.9	37.1	38.7	40.6
Spring . . .	45.5	44.8	45.3	45.4	44.5	43.7	42.5
Summer	62.2	62.8	63.4	62.4	61.8	59.8	57.6
Autumn .	44.8	43.7	48.6	50.5	52.1	52.6	53.3

Average Temperature Readings Taken at Lincoln, Nebraska.[2] Averages of Twelve Years, 1890–1902 (in Degrees Fahrenheit)

	Air	1 Inch Deep	3 Inches Deep	6 Inches Deep	12 Inches Deep	24 Inches Deep	36 Inches Deep
Winter . . .	25.9	28.8	28.8	29.5	32.2	36.3	39.1
Spring . . .	49.9	54.8	53.6	51.6	48.5	45.7	44.3
Summer . . .	73.8	83.0	80.0	79.1	73.8	69.0	66.2
Autumn . . .	53.9	56.4	57.6	57.1	57.5	59.3	60.3

[1] Schulze, B., and Hornetter, H. Beobachtungen über Temperaturverhältnisse der Bodenoberfläche und verschiedener Bodentiefen. Internat. Mitt. für Bodenkunde, Band II, Heft 2-3, Seite 133–148. 1912.

[2] Swezey, G. D. Soil Temperatures at Lincoln, Nebraska. Nebraska Agr. Exp. Sta., 16th Ann. Rept., pp. 95–108. 1903.

These average readings, taken at different points, are supported by the data of other observers.[1] It is apparent that seasonal variation of soil temperature is considerable, even at the lower depths. The surface layers of soil seem to vary nearly in accord with the air temperature, and therefore exhibit a greater fluctuation than the subsoil. In general the surface soil is warmer in spring and summer than the lower layers, but cooler in fall and winter. The following data taken at Lincoln, Nebraska, may be of interest: —

AVERAGE MONTHLY TEMPERATURE READINGS[2] TAKEN AT LINCOLN, NEBRASKA. AVERAGE OF TWELVE YEARS

	Air	1 Inch Deep	3 Inches Deep	6 Inches Deep	9 Inches Deep	12 Inches Deep	24 Inches Deep	36 Inches Deep
January	25.2	27.3	27.8	28.6	30.0	31.2	35.4	38.5
February	24.2	27.7	27.3	27.8	28.3	30.2	33.5	36.5
March	35.8	39.3	37.3	36.0	35.6	35.4	35.4	36.8
April	52.4	57.5	56.0	53.3	50.6	48.3	45.6	43.8
May	61.9	68.7	67.5	65.1	63.3	60.7	56.2	53.3
June	71.0	78.1	78.0	75.7	73.8	69.9	64.6	61.3
July	76.0	85.3	83.6	81.6	79.3	75.7	70.2	67.4
August	74.5	82.9	81.3	80.1	78.5	75.7	72.2	69.6
September	67.6	72.8	73.4	73.0	70.7	69.2	68.7	67.6
October	55.5	56.7	58.4	57.8	58.3	57.8	60.0	61.3
November	38.7	38.7	40.9	41.5	43.3	44.7	49.2	52.2
December	28.3	31.6	31.4	32.0	33.4	35.2	40.1	43.3
Average	50.9	55.5	55.3	54.8	53.8	52.9	52.6	52.[illegible]
Range	51.8	57.8	56.3	53.8	51.0	45.5	38.7	34.0

[1] Ebermayer, E. Untersuchungen über das Verhalten verschiedener Bodenarten gegen Wärme. Forsch. a. d. Geb. d. Agri-Physik, Band 14, Seite 195-233. 1891.

[2] Swezey, G. D. Soil Temperatures at Lincoln, Nebraska. Nebraska Agr. Exp. Sta., 16th Ann. Rept., pp. 95-102. 1903.

The upper soil layers vary in accordance with the air temperature, the maximum and the minimum occurring in the same month. A lagging (see Fig. 53) is apparent in the subsoil, due to the slow response of this area to the heat penetrating from above. These figures also show the surface soil to be warmer in spring and summer, and cooler in winter and fall, than the lower depths. The surface soil not only never falls as low in temperature as the air, but reaches a higher point in summer. This is shown in the range of the air and soil temperatures. The range for the air is 51.8°, while that for the soil is 57.8°, 56.3°, 53.8°, 51.0°, 45.5°, 38.7°, and 34.3°, respectively, for the depths ranging from 1 inch to 36 inches. While this range of soil temperature is greater in the aggregate than that of the air, the changes are much slower and often extend over a number of days, while the air may vary many degrees in an hour.

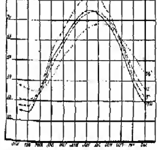

Fig. [illegible].—Curves showing the average monthly temperature readings at various soil depths. Average of twelve years, Lincoln, Nebraska.

The daily and hourly temperature of the air and the soil may be fairly constant or rather variable, according to conditions. On days of sunshine, however, consistent changes may be expected. The air temperature rises from morning until about two o'clock, when the maximum is reached. It then falls rapidly. The soil, however, does not reach its maximum temperature until later in the afternoon, due to the lagging so apparent in soil temperature changes. This lagging is greater in the lower layers than at the surface. The following data,[1] taken on a bright day on May 26 in Germany, illustrate the ordinary differences that may be expected in soil and air temperatures: —

HOURLY TEMPERATURES TAKEN IN GERMANY ON MAY 26, 1884, ON A LOAM SOIL AT 4-INCH DEPTH (IN DEGREES FAHRENHEIT)

Hour	Air	Bare Soil
Midnight	55.4	63.5
2 A.M.	54.2	60.4
4	52.7	58.6
6	57.6	57.0
8	70.4	58.4
10	82.0	63.3
Noon	83.5	69.8
2 P.M.	85.6	74.8
4	84.3	77.0
6	78.1	77.7
8	68.7	73.9
10	65.1	69.8

[1] Wollny, E. Untersuchungen über den Einfluss der Pflanzendecke und der Beschattung auf die Physikalischen Eigenschaften des Bodens. Forsch. a. d. Geb. d. Agri.-Physik, Band 6, Seite 197-256. 1883.

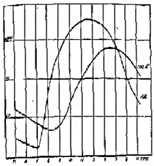

FIG. 54.—Curves showing the hourly temperatures of bare soil at a depth of four inches and of the air above the soil. May 26, Germany.

The temperature of the soil at the surface may often exceed that of the air, and the amount of daily fluctuation may be greater; but for the lower depths the temperature curve flattens out. The subsoil shows but little daily, and even monthly, variation, and is affected only by seasonal changes.

228. **Control of soil temperature.** — The means of practical control and modification of soil temperature are those commonly in vogue in good soil management. The most important factor is, of course, soil moisture. Good drainage, proper tilth developed by deep plowing, plenty of lime, and sufficient organic matter, favor optimum moisture conditions. Such moisture regulation means a lowered specific heat and good conductivity. The use of a soil mulch or an artificial covering not only will check evaporation but will markedly retard loss of heat by radiation. Any farmer who so controls his soil

moisture that optimum conditions as far as the plant is concerned may be obtained, should have no fear of a poor utilization of heat.

The increase of soil humus, of course, may act directly in heat control by darkening the color and increasing absorption. A soil mulch, being dry, not only checks evaporation but lowers radiation while increasing absorption. Any methods of handling the land which tend to better the physical condition of the soil and increase its tilth tend also toward a proper heat control at the same time. The whole question may be summarized by saying that if a farmer adopts a proper system of moisture control and at the same time employs methods that tend always toward a better physical condition of the soil, the problem of control of soil heat will be automatically solved. He will then have brought about the best conditions for heat absorption and will have facilitated conduction and convection, while at the same time retarding losses by evaporation and radiation.

CHAPTER XV

AVAILABILITY OF PLANT NUTRIENTS AS DETERMINED BY CHEMICAL ANALYSIS

Fortunately for mankind, only an exceedingly minute proportion of the soil is at any one time soluble in water or in the aqueous solutions with which it is in contact. It is this great degree of insolubility that gives the soil its permanence, for in humid regions, without this property, it would be rapidly carried away in the drainage water. The portion of the soil that is soluble in the various natural solvents with which it comes in contact furnishes mineral food materials for plants. The great mass of soil, which is relatively insoluble, is constantly subjected to natural processes which very slowly bring its constituents into solution. The agents that are concerned in the decomposition of rock also act on the soil to bring about its further disintegration, and thereby render it more soluble; while added to these are the operations of tillage, which contribute to the same end.

Only the surfaces of the soil particles come into contact with the decomposing agents, and hence it is the surface matter of the particles that gradually goes into solution. The factors that determine how rapidly solution shall proceed are: (1) the amount of surface exposed, which, as has been seen, varies with the size of the particles; (2) the composition of the particles; (3) the strength of the decomposing and solvent agencies. Were it not for this

process, there would soon be no mineral food available to plants, as drainage water and the growth of crops take up relatively large quantities of these substances each year; but in spite of this loss the soil is able to provide at least some plant-food material for each crop, when called upon by the plant.

229. Solubility of the soil in various solvents. — For purposes of analyses that are intended to show the amounts of mineral plant-food materials in a soil, any one of several different solvents may be used. These solvents differ in strength, and consequently the percentages of the various constituents obtained from samples of the same soil are different for each solvent. A chemical analysis of a soil is a determination of the quantities of the constituents that have been dissolved in the solvent used. Therefore it will readily be seen that the interpretation of a chemical analysis must depend largely on the nature of the solvent, and, unless the solvent is equivalent in its action to some process or processes in nature, the results must be entirely arbitrary.

The methods that have been used for obtaining solutions of the soil for analysis may be grouped as follows: —

1. Complete solution of the soil.
2. Partial solution with strong acids.
3. Partial solution with weak acids.
4. Extraction with water.

230. Complete solution of the soil. By the use of hydrofluoric and sulfuric acids and by fusion with alkalies, the entire soil mass may be decomposed and all its inorganic constituents determined.[1] Such an analysis shows

[1] Wiley, Harvey W. Principles and Practice of Agricultural Chemical Analysis, Vol. 1, pp. 308–309. 1906.

the total quantity of the plant-food materials except nitrogen, which is never determined in any of the acid solutions but by a separate process.[1] A deficiency of any particular substance may be discovered in this way, but nothing can be learned as to the ability of the plant to obtain nutriment from the soil. A rock may show as much mineral plant-food material as a rich soil. This method of analysis is used only to ascertain the ultimate limitations of a soil or its possible deficiency in any essential constituent. Results of such analyses are to be found in paragraphs 46, 48, 52, 53 of this text.

231. **Partial solution with strong acids.** While sulfuric, nitric, and hydrochloric acids have all been used as solvents,[2] the one most commonly employed is hydrochloric acid of 1.115 specific gravity.[3] It has been used to such an extent that it may be considered the standard solvent, and a statement of a chemical analysis of a soil in this country may be considered as based on this solvent unless otherwise stated.

[1] Official and Provisional Methods of Analysis. U. S. D. A., Bur. Chem., Bul. 107 (revised), p. 19. 1908.

[2] Analyses using concentrated mineral acids on the same soil. From Snyder, Harry. Soils. Minnesota Agr. Exp. Sta., Bul. 41, p. 61. 1895.

	Hydrochloric	Nitric	Sulfuric
Total insoluble percentage	81.20	83.45	80.45
Potash percentage	0.42	0.30	0.52
Lime percentage	0.55	0.30	0.53
Magnesia percentage	0.40	0.32	0.52
Phosphoric acid percentage	0.13	0.23	0.26
Sulfuric acid percentage	0.08	0.08	0.10

[3] Official and Provisional Methods of Analysis. U. S. D. A., Bur. Chem., Bul. 107 (revised), pp. 14–18. 1908.

An analysis by this method is supposed to show the proportion of plant-food materials in a soil that are in a condition to be ultimately used by plants at the time when the analysis is made, and the plant-food materials that are not dissolved by treatment with hydrochloric acid are assumed to be in a condition in which plants cannot use them. The difficulty with this assumption is that, while treatment with hydrochloric acid of a given strength marks a definite point in the solubility of the compounds in the soil, it does not bear a uniform relation to the natural processes by which these compounds become available to the plant.

In the case of most soils a large proportion is not decomposed by treatment with strong hydrochloric acid, and the portion that is dissolved may contain a larger or a smaller quantity of the agriculturally important elements, depending on the character of the soil. Thus if calcium is present as a phosphate, a larger proportion will be dissolved by the acid than if it is in the form of silicate. The form in which potassium occurs also influences greatly the amount shown by analysis.

Snyder[1] has analyzed a number of soils by means of digestion with strong hydrochloric acid, and has then decomposed the acid-insoluble residue by fusion and determined its composition. Veitch[2] has analyzed soils by the hydrochloric acid method and by means of complete solution. A few examples are given below to show how soils may vary in the solubility of their constituents in strong hydrochloric acid: —

[1] Snyder, Harry. Soils. Minnesota Agr. Exp. Sta., Bul 41, p. 35. 1895.

[2] Veitch, F. P. The Chemical Composition of Maryland Soils. Maryland Agr. Exp. Sta., Bul. 70, p. 103. 1901.

PERCENTAGE OF CONSTITUENTS NOT SOLUBLE IN HCl, 1.115 SP. GR.

	SOIL FROM MINNESOTA			SOIL FROM [illegible]		
	Fair Grove	[illegible]	Experiment Station	[illegible]	[illegible]	[illegible] River Vale
Potash	94	81	83	95	67	73
Lime	25	04	41	90	82	27
Magnesia	58	76	38	34	30	28
Phosphoric anhydride	40	45	18	66	15	0
Sulfuric anhydride	74	90	20	.	—	—

230. **Significance of a strong hydrochloric acid analysis.** — This method of analysis was originally thought to give some indication of both the permanent fertility and the immediate manurial needs of a soil; but for each question the accuracy of the deductions is limited by a number of conditions that make it impossible invariably to predict from an analysis how productive a soil may be or what particular manure may be profitably applied. It is very apparent that the chemical composition of a soil is only one of the many factors affecting its productiveness. Unfortunately, not all the factors are understood, and consequently these unknown ones cannot be determined either qualitatively or quantitatively. If it ever becomes possible to determine quantitatively all the factors entering into soil productiveness in the field condition, the problem will be solved.

231. **Relation of texture to solubility.** The ratio of sand to clay in a soil, and the distribution of the fertilizing materials in these constituents, will affect the mini-

mum quantity of any constituent required to produce a good crop. Hilgard has shown that the addition of four or five volumes of quartz sand to one volume of a heavy, but highly productive, black clay soil greatly increased the productiveness, while diluting the potash content of the mixture to 0.12 per cent and the phosphoric acid to 0.03 per cent. It is evident that in this soil the plant-food materials were in a condition to be easily taken up by the plant when the physical condition of the soil was suitable.

If these small quantities of food elements had been distributed in the sand particles as well as in the original clay, the result would doubtless have been different. Suppose, for example, that fifty per cent of the potash and phosphoric acid had been in the sand particles and the remainder in the clay; in that case the former, in a soil exposing much the less surface to dissolving liquids, would be proportionately less soluble, and as the minimum quantity is approached, as shown by the more dilute soil's yielding less than the other, the effect would doubtless have been to decrease the production. In some soils, particularly those of arid regions, the larger particles may carry much of the mineral nutrients, in which case it is quite evident that a higher percentage of fertility is required than in soils carrying the plant-food material largely in the small particles.

234. Nature of the subsoil. — The nature and composition of the subsoil is naturally a factor in determining soil-productiveness, and must be considered as well as the top soil. An impervious subsoil, or a very loose sandy one, will confine the productive zone largely to the topsoil and hence require a greater proportionate amount of fertility in that part of the soil.

296. **Calcium carbonate.** — A determination of the amount of calcium present as a carbonate is important as an aid in the interpretation of an analysis of the soil. Lime not so combined is generally in the form of a silicate, or possibly a phosphate. If there is a large quantity of calcium carbonate in a soil, the potash, phosphoric acid, and nitrogen are likely to be more readily soluble, and smaller quantities are sufficient for crop growth, than if the calcium is not found in this form. The effect of the carbonate of lime on the nitrogen[1] compounds is to furnish a base for the acids produced in the formation of nitrates, and its presence promotes this process. It probably replaces potassium in certain compounds where otherwise it would be secured with more difficulty. It insures the presence of some phosphates of lime, in which form phosphorus is more soluble than when combined with iron. The form of the manures to be used on the soil will also depend in large measure on the presence or the absence of calcium carbonate. For example, where calcium carbonate is deficient, steamed bone or Thomas slag are likely to be more profitable than superphosphate, and nitrate of soda than sulfate of ammonium. Finally, the absence of calcium carbonate indicates the need of liming, and if the analyses show a considerable quantity of potash and phosphoric acid, but practice shows these materials to be somewhat deficient, it is probable that liming will be very beneficial, and that manures carrying these substances will not be so essential as the chemical analysis would indicate. It must be stated, however, that there are cases in which these deductions do not hold, owing to the intervention of other factors.

[1] Not determined in the hydrochloric acid extract.

236. Deficiency of ingredients and manurial needs. — Many standards have been set for the minimum quantity of each of the important soil constituents that must be present in order to insure a productive soil. Experience has shown, however, that no definite standards hold for all soils. By comparing analyses of soils of known productivity with that of a soil under investigation it is an easy matter to ascertain whether the soil contains a large quantity of each agriculturally important ingredient; but when the quantity of any constituent is low, it becomes a difficult matter to tell how this will affect the agricultural value of the soil. Some soils will be productive with 0.05 per cent of phosphoric anhydride, while others are unproductive when all the plant nutrients are present in ample quantity.

The fact that the degree of productiveness of a soil cannot always be gauged by its analysis gives rise to a similar uncertainty with regard to its manurial needs. A soil may contain potassium in very large quantities, sufficient to produce crops for hundreds of years, as indicated by a strong hydrochloric acid analysis, and yet a potassium salt may be used with profit. On the other hand, it is evident that as the content of any constituent becomes less, the probable need for its application becomes greater, and a knowledge of the composition of the soil thus suggests a practice without assuring its success. An analysis of the hydrochloric acid extract, therefore, cannot be taken as an infallible guide to the fertilizer needs of a soil, and of itself should not be relied upon; but in connection with other knowledge, particularly that derived from fertilizer tests, it may be useful.

237. Partial solution with weak acids. — The difficulty in judging of the properties of a soil from the results of

a strong hydrochloric acid analysis has led to the use of weak acids for obtaining the solution. These weak acids dissolve much less of the soil constituents than do the strong acids, and the portion so dissolved is supposed to represent more nearly the amount that the plant can make use of. Both dilute organic acids and dilute mineral acids have been used. Among the former are citric, acetic, oxalic, and tartaric acids. The assumption on which the use of the organic acids is based is that they correspond to the solvent agents in the soil combined with the solvent action that the plant is supposed to possess, and thus dissolve from the soil the quantities of nutrients that the plant could take up if it came in contact with all the soil particles to a depth represented by the sample analyzed.

238. Advantages in the use of dilute acids. — The action of each of these dilute acids on the same soil does not give equal quantities of the various constituents in solution. The dilute acids naturally dissolve a much smaller amount of material from the soil than does strong hydrochloric acid. The dilute acids permit the detection of smaller quantities of easily soluble phosphoric acid and potash than does the latter, larger quantities of soil being used. For example, a chemical analysis of the strong hydrochloric acid solution is very likely not to show any increase in the phosphorus or potassium in a soil that may have been abundantly manured with these fertilizers and its productiveness greatly increased thereby. This is because the amount of plant-food material added is so small in comparison with the weight of the acre of soil nine inches deep over which it is spread that the increase in percentage may well come within the limits of analytical error. An acre of soil nine inches deep weighs about

2,500,000 pounds. If to this there is added a dressing of 2500 pounds of phosphoric acid fertiliser containing 400 pounds of phosphoric acid, it would increase the percentage of that constituent in the soil only 0.016 per cent — a difference that could not be detected by the analysis of the hydrochloric acid solution.

239. The one-per-cent citric acid method. — This method was proposed by Dyer[1] and was shown by him to give results with Rothamsted soils that permitted of an accurate estimation of their relative productivity. Dyer adopted the one-per-cent strength as the result of an investigation in which he determined the acidity of the juices in the roots of over one hundred species or varieties of plants representing twenty different natural orders. The average acidity of the juices of the twenty orders, calculated to crystallized citric acid, was 0.91 per cent, which led Dyer to adopt a strength of 1 per cent. It must be said, however, that the different varieties varied greatly in this respect, some having ten times as much acidity as others. The implication is that plants produce a solvent action on a soil in proportion to the acidity of their juices, but an examination of Dyer's figures does not show that the size of the crop ordinarily produced by the plants tested would in many cases correspond to the acidity of these juices. Thus, of the Cruciferæ the horse-radish has several times the acidity of the Swedish turnip or of the field cabbage, although the crop produced by the former is much less than that of the latter.

240. Usefulness of the citric acid method. — As shown by Dyer, the use of a one-per-cent solution of citric

[1] Dyer, Bernard. "On the Analytical Determination of Probably Available 'Mineral' Plant Food in Soils. Jour. Chem. Soc., Vol. LXV, pp. 115–167. 1894.

acid is well adapted to show the amount of easily soluble phosphoric acid and potash in certain soils, but for other soils it has failed to give satisfaction in the hands of a number of analysts. It is doubtless best suited to soils rich in calcium and low in iron and aluminium.

The reason urged by Dyer for the superiority of the citric acid method over the hydrochloric acid extraction is that soils, shown by experience to need phosphoric manures, yielded a relatively much greater quantity of phosphorus to citric acid than to hydrochloric acid when compared with soils not needing this element.

The application of both the hydrochloric and citric acid methods to a soil, when used to supplement each other, may add greatly to a knowledge of the potential and present productiveness of the soil.

According to Dyer,[1] for cereals and for most other crops there should be present in a soil at least .01 per cent of phosphoric acid, soluble in one-per-cent citric acid. A soil containing less than this quantity is deficient in phosphoric acid, unless this acid exists largely in the form of ferric or aluminium phosphate, which is not readily soluble in citric acid but is fairly available to the plant. Sod land contains organic compounds of phosphorus that are readily available to the plant; hence such soil, to indicate sufficiency, should show by analysis more than 0.01 per cent of phosphoric acid. The quantity of potash soluble in the same solvent should also be not less than 0.01 per cent in arable land.

[1] Dyer, Bernard. A Chemical Study of the Phosphoric Acid and Potash Contents of the Wheat Soils of Broadbalk Field, Rothamsted. Philosoph. Trans. Royal Soc. London, Series B, Vol. 194, pp. 235–290. 1901.

241. Dilute mineral acids. — Of the mineral acids in a diluted form used for extracting soils, those that have received the most attention are one-fifth normal nitric[1] or hydrochloric acid and one two-hundredth normal hydrochloric acid.[2] The methods employing these solvents are admittedly empirical. There is no natural relation between these solvents and the processes by which the plant obtains its nutriment from the soil.

The solvent that has received the most attention is one-fifth normal nitric acid. In ease of manipulation this is preferable to the one-per-cent citric acid, which is rather tedious to work with. It has been used nearly as extensively in this country as the latter has in Great Britain. Its use has been confined largely to the determination of the readily available phosphorus and potassium in the soil, as has the citric acid method. It is obvious that some minerals are more readily soluble than are others, and for that reason the method will distinguish between phosphorus and potassium in different forms. The calcium phosphates are supposed to be entirely soluble in this solvent. According to Fraps[3] it dissolves iron and aluminium phosphates to only a slight extent, thus distinguishing between these forms of phosphorus. Fraps finds also that no potassium is removed from orthoclase and microcline, that less than ten per cent is dissolved

[1] Official and Provisional Methods of Analysis. U. S. D. A., Bur. Chem., Bul. 107 (revised), p. 18. 1908.

[2] Wiley, H. W. Principles and Practice of Agricultural Analysis, pp. 394-400. Easton, Pennsylvania. 1906.

[3] Fraps, G. S. Active Phosphoric Acid and Its Relation to the Needs of the Soil for Phosphoric Acid in Pot Experiments. Texas Agr. Exp. Sta., Bul. 126, pp. 7-73. 1910. Also, The Active Potash of the Soil and Its Relation to Pot Experiments. Texas Agr. Exp. Sta., Bul. 145, pp. 5-39. 1912.

from glauconite and biotite, and that from fifteen to sixty per cent is dissolved from muscovite, nephelite, leucite, apophyllite and phillipsite.

There are several factors, however, that make the use of one-fifth normal nitric acid an uncertain guide to the available phosphorus and potassium in the soil. When a soil is treated with the acid some of it is neutralized by the reactions that result and thus its strength is lessened. This may have no relation to the quantities of phosphorus or potassium dissolved. Some analysts correct for the neutralization and some do not. Again, as with strong hydrochloric acid, the degree of solubility of the soil constituents in the nitric acid may not correspond with the ability of the plant to obtain these substances. With this, as with the other methods discussed, the objection holds that the result cannot be taken as an infallible guide to the productiveness of a soil, or to its fertilizer needs; but each of the methods affords some information in regard to a soil, and is thus of value.

242. Extraction with an aqueous solution of carbon dioxide. – As carbon dioxide is a universal constituent of the water of the soil, and without doubt a potent factor in the decomposition of the mineral matter, it has been proposed to use a solution of carbon dioxide as a solvent in soil analysis. The amounts of soil constituents taken up by this solvent are much less than are taken up by any of the others heretofore mentioned, but all mineral substances used by plants are soluble in it to some extent. The amount of phosphorus is so small as to make its detection by the gravimetric method difficult. Like other methods employing very weak solvents, this method is open to the objection that the extraction fails to remove a considerable portion of the dissolved matter that is

retained by adsorption, and as this varies with soils of different texture a fair comparison of such soils is impossible.

243. Extraction with pure water. — When soil is digested with distilled water, all the mineral substances used by plants are dissolved from it, but in very small quantities. It has been proposed to use this extract for soil analysis on the ground that it involves no artificial solvent the presence or amount of which in the soil is doubtful, but shows those substances that are undoubtedly in a condition to be used by plants. By determining the water content of the soil and using a known quantity of water for the extraction, the percentage of the various constituents in the soil water or in the dry soil may be calculated.

The substances dissolved from the soil by extraction with distilled water are probably only those contained in the soil-water solution, including a part of the solutes held by adsorption. The aqueous extract does not contain the entire quantity of the nutritive salts in solution in the soil water, and hence is not a measure of the fertility held in that form. An undetermined quantity of nutrients is retained in the water, in the very small spaces and on the surface of the soil particles. It is, however, a fair comparative measure of the content of available nutrients.

244. Influence of absorption. — The quantity of extracted material depends on the absorptive properties of the soil and on the amount of water used in the extraction, or on the number of extractions. Analyses of the aqueous extract of a clay and of a sandy soil on the Cornell University farm serve to illustrate the greater retentive power of the former for nitrates. Sodium nitrate was

applied to a clay soil and to a sandy loam soil at the rate of 640 pounds to the acre. Analyses of aqueous extracts some ninety days later showed the following: —

Kind of Soil	Fertilizer	Nitrates in Soil (Parts per million)
Clay	Sodium nitrate	7.6
Clay	No fertilizer	1.8
Sandy loam	Sodium nitrate	152.0
Sandy loam	No fertilizer	28.7

There was apparently a much greater retention of nitrate by the clay soil, as shown by a comparison of the fertilized and the unfertilized plats on both soils.

Schulze[1] extracted a rich soil by slowly leaching 1000 grams with pure water, so that one liter passed through in twenty-four hours. The extract for each twenty-four hours was analyzed every day for a period of six days. The total amounts dissolved during each period were as follows: —

Successive Extractions	Total Matter Dissolved (Grams)	Volatile (Grams)	Inorganic (Grams)
First	0.535	0.340	0.195
Second	0.120	0.057	0.063
Third	0.251	0.101	0.150
Fourth	0.203	0.083	0.120
Fifth	0.260	0.082	0.178
Sixth	0.200	0.077	0.123

[1] Schulze, F. Ueber den Phosphorsäure-Gehalt des Wasser-Auszugs der Ackererde. Landw. Vers. Stat., Band 6, Seite 409-413. 1864.

It will be noticed that the dissolved matter, both organic and inorganic, fell off markedly after the first extraction, which was larger because of the matter in solution in the soil water. Later extractions were doubtless supplied largely from the substances held by adsorption, which gradually diffuse into the water extract as the tendency to maintain equilibrium of the solution overcomes the adsorptive action. With the removal of the adsorbed substances, the equilibrium between the soil particles and the surrounding solution is disturbed, solvent action is increased, and more material gradually passes from the soil into the solution. In this way the uniform and continuous body of extractives is maintained.

245. Other factors influencing extraction. — For purposes of soil analysis, the quantity of water used for extraction must be placed at some arbitrary figure, and this is open to the objection that it does not represent accurately the soil-water solution. Analyses of soils of different types are not comparable, and the water extract cannot be considered as measuring the concentration, or even the composition, of the solution existing between the root hair and the soil particles. However, for studying some of the changes which go on in the soil and which are detectable in the soil-water solution, the practice may be followed to advantage.

246. The soil solution *in situ*. — It has already been pointed out that the interstitial spaces of any arable soil contain more or less water all the time; that there is a constant tendency for this water to assume the capillary condition owing to the gravitational movement of free water; and that the normal evaporation of moisture from the soil tends to reduce the capillary film to the condition of hygroscopic water (par. 132). As the movement

of free water is comparatively rapid and that of capillary water relatively slow, the soil moisture supply is usually somewhere between the point of lento-capillarity and free water. In this condition each particle or aggregation of particles is enveloped in a thin moisture film, and this film water is constantly in motion although the movement is rather slow.

Salts are more or less soluble in pure water; and in soil water, charged as it always is with carbon dioxide, they are still more readily soluble. Consequently the moisture films constantly tend to approach a state of equilibrium with respect to the water-soluble matter in the soil particles. If plants are entirely dependent for their mineral nutrients on the supply in the soil-water solution, the strength of this solution becomes an important matter. The supply of mineral nutrients for higher plants will be discussed later (par. 339). Even if the plant itself has no influence on the supply of mineral nutrients that go into solution, the quantity of food that it finds in the soil solution already prepared for its use must constitute an important factor in its growth.

Unfortunately there is no adequate method of ascertaining the strength of the solution. Attempts have been made to remove this solution from the soil, but it is altogether unlikely that the analyses of the liquid obtained represent the composition of the soil solution, because of the very small quantity of the liquid available for analysis and also because of the uncertainty that the sample obtained was representative of the soil solution.

241. Devices for obtaining a soil solution. — An attempt by Briggs and McLane[1] to sample the soil solution

[1] Briggs, Lyman J., and McLane, John W. The Moisture Equivalent of Soils. U. S. D. A., Bur. Soils, Bul. 45, pp. 6-8. 1907.

involved the use of centrifugal motion, which developed a force of two or three thousand times that of gravitation. When the soil contained a rather large quantity of capillary water, a small amount of it could be removed in this way.

Another device, by Briggs and McCall,[1] consists of a close-grained, unglazed, porcelain tube, closed at one end and provided at the other with a tubulure, by which it can be connected with an exhausted receiver. This tube is moistened and buried in the soil. If the moisture content of the soil is sufficient to reduce the pressure of the capillary water surface in the soil to less than the difference between the pressure inside and outside of the tube, there will be a movement of water inward. This water may be collected and analyzed.

More recently Van Suchtelen has used another method to obtain the soil solution.[2] He replaces the soil water by means of paraffin in a liquid state, at the same time subjecting the soil to suction on a filter. The displaced water is considered to represent the soil solution.

246. Composition and concentration of the soil solution. — It has generally been held that because some soils are more productive than others, and because fertilizers containing soluble salts frequently increase the yields of crops, the soil solution in the better-yielding soils is more concentrated, at least as regards plant nutrients, than is that in the poorer soils. The argument is, of course,

[1] Briggs, L. J., and McCall, A. G. An Artificial Root for Inducing Capillary Movement of Soil Moisture. Science, N. S., Vol. 20, pp. 566–569. 1904.

[2] Van Suchtelen, F. H. H. Methode zur Gewinnung der natürlichen Bodenlösung. Jour. f. Landw., Band 60, Seite 369–370. 1912.

based on the assumption that, other things being equal, plant growth is a function of the concentration of the plant nutrients in the soil solution. According to this conception, increased or decreased soil fertility is reflected in the composition and concentration of the soil solution, and this in turn in crop yields. The soil solution is therefore a variable quantity, and, to some extent at least, within the control of man. An elaborate explanation for the responsiveness of the soil solution has been worked out by Van Bemmelen and his school.

249. Variability in composition and concentration of the soil solution.—The process of rock weathering has, according to Van Bemmelen,[1] Biltz,[2] and others, resulted in deep-seated chemical changes in some of the mineral constituents of the soil, whereby there are formed complex colloidal silicates which, in the form of gels, cover the surfaces of the soil particles. These colloidal complexes may contain iron, aluminium, calcium, magnesium, potassium, phosphorus, and other substances, which are absorbed from the different electrolytes as ions or as salts and depend in quantity on the concentration of the solution from which they are absorbed. They therefore act like solid solutions, whose composition changes with every change in the concentration of the liquid solution that comes in contact with them. This relation of the colloidal complexes to the soil water with which they come in contact is essentially different from that of the

[1] Van Bemmelen, J. M. Beiträge zur Kenntniss der Verwitterungsprodukte der Silikate in Ton, Vulkanischen, und Laterit-Böden. Zeit. f. Anorganische Chemie, Band 42, Seite 265-324. 1904.

[2] Biltz, W. Ueber die Gegenseitige Beeinflussung Colloidal Gelöster Stoffe. Ber. deutsch. chem. Gesell., Band 37, Seite 1095-1116. 1904.

pure minerals, as they are not true chemical combinations. The organic matter in the soil adds another class of colloidal matter; so that, in the opinion of Van Bemmelen,[1] the colloidal silicates and the colloidal humus form, in various proportions, a mass of colloidal complexes that control the composition of the soil solution. The colloidal condition of this material is readily decomposable under variations in temperature and concentration of solutions, and would doubtless be in a state of constant transition in the soil.

This conception of the soil surface would account for changes in the concentration of the soil solution due to the application of soluble fertilizers, and would also explain the continued effect of such fertilizers on the theory that they are absorbed by the colloidal complexes and redissolved as the soil solution tends to become more dilute.

A somewhat different view has been taken by Whitney and Cameron, who hold that the composition and concentration of the solution in all soils is practically the same. Their conception, according to a recent paper by Cameron,[2] appears to differ from that of Van Bemmelen in assuming that the soil water is in contact with the soil particles for such a short time that the quantity of matter that goes into solution is too slight to bear any relation to the total quantity of soluble matter in the soil. The soil solution does not come into equilibrium with the soil mass, nor even approximate such a condition. The

[1] Van Bemmelen, J. M. Die Zusammensetzung der Ackererde. Landw. Vers. Stat., Band 37, Seite 347-373. 1890.

[2] Cameron, F. K. Concentration of the Soil Solution. Original Communications, Eighth International Congress of Applied Chem., Vol. 15, pp. 43-48. 1912.

solution being similar in all soils, it follows that the relative productiveness of different soils bears no relation to the supply of soluble nutrients, but must be due to other factors. Hence soluble fertilizers increase plant growth, not by supplying a greater quantity of plant nutrients, but through other effects on the soil — as, for instance, their favorable influence on tilth, or through the destruction of toxic matter.

250. Discussion of the theories regarding soil solutions. The difficulty in securing a true sample of the soil solution as it exists *in situ* complicates any attempt to ascertain how these theories comport with the actual condition of the soil solution. A number of attempts have been made to throw light on this subject, but none of the data obtained is of a nature to definitely prove the correctness of either theory. The evidence, so far as it goes, indicates that the water extract of soils differs in concentration in different soils, and is increased, under some conditions, by large and continued applications of soluble fertilizers. There can be no doubt, moreover, that plant growth in properly balanced nutrient solutions increases with the concentration of the solution up to several thousand parts to the million, as has been demonstrated by many experiments.

One rather convincing experiment may be quoted. Hall, Brenchley, and Underwood[1] analyzed the water extract from certain plots on the Rothamsted Experiment Station farm, the fertilizer treatment and the yields of which had been recorded for a long term of years.

[1] Hall, A. D., Brenchley, W. E., and Underwood, T. M. The Soil Solution and the Mineral Constituents of the Soil. Philosoph. Trans. Royal Soc. London, Series B, Vol. 204, pp. 179–200. 1913.

Complete analyses of the soil from the several plats were also made:—

Yields of Crops, and Composition of Soil and Water Extract of Soil, on Rothamsted Experiment Station Farm

	Yield to the Acre (Pounds)	Complete Analysis		Water Extract	
		P_2O_5 (percentage)	K_2O (percentage)	P_2O_5 (p. p. m.)	K_2O (p. p. m.)
Unmanured . . .	1,376	0.099	0.153	0.695	3.40
$N + P_2O_5$ . . .	3,372	0.173	0.248	3.930	3.88
$N + K_2O$ . .	2,995	0.100	0.257	0.808	30.33
Complete fertilizer	5,087	0.182	0.326	4.025	24.03
Farm manure . .	6,164	0.176	0.167	4.463	26.45

A similarly treated set of plats, which had been planted to another crop and analyzed as were these, gave similar results. It is a very striking example of the effect of long-continued treatment of the soil with a certain fertilizer on the composition of the water extract. The subject, however, must be investigated further, as it is of fundamental importance to a knowledge of the properties of soils.

CHAPTER XVI

THE ABSORPTIVE PROPERTIES OF SOILS

If the brown water extract from manure is filtered through a clay soil not containing soluble alkalies, the filtrate will be nearly colorless. Many solutions of dye-stuffs are affected in the same way. Solutions of alkali or alkaline earth salts are more or less modified by this operation, the bases being retained by the soil to a greater extent than are the acids. Thus, when a solution of the nitrate, sulfate, or chloride of any one of these bases is filtered through the soil, a part of the base is absorbed by the soil, while most of the acid comes through in the filtrate. If these bases are in the form of phosphates or silicates, not only the base is absorbed, but the acid as well.

251. Substitution of bases. — Associated with the absorption of the base from solution, there is liberation of some other base from the soil, which combines with the acid in the solution and appears in the filtrate as a salt of that acid.

When absorption takes place from solution, the base is never entirely removed, no matter how dilute the solution may be. A dilute solution of potassium chloride filtered through a soil will produce a filtrate containing some calcium, magnesium, or sodium chloride, or all these salts, and some potassium chloride. The more dilute the solution, the larger will be the proportion re-

tained, but the less the total quantity absorbed. Peters[1] treated 100 grams of soil with 250 cubic centimeters of a solution of potassium salts, and found that the potassium of different salts was retained in different proportions, and that the stronger solutions lost relatively less than the weaker, while more potassium was removed from the stronger solutions.

[illegible]	[illegible] Normal	[illegible] Normal
	Grams K_2O absorbed	Grams K_2O absorbed
KCl	0.3124	0.1950
K_2NO_3	0.3362	0.2038
K_2SO_4	0.5747	0.3134

The same bases are not always absorbed in the same proportion by different soils; one soil may have a greater absorptive power for potassium, while another may retain relatively more ammonia. They seem to be interchangeable, as any absorbed base may be released by another in solution. The absorptive power of a soil for certain bases is reflected in the composition of the drainage water from the soil. The composition of the drainage water varies with different soils, and a soluble fertilizer applied to one soil will have a different effect on the composition of the drainage water than if applied to a different soil. This is well illustrated from lysimeter experiments by Gerlach[2] at Bromberg. Several soils were used,

[1] Peters, E. Ueber die Absorption von Kali durch Ackererde. Landw. Vers. Stat., Band 3, Seite 113-151. 1860.

[2] Gerlach, Dr. Uber die durch sickerwasser dem Boden Entzogenen Menge Wasser und Nahrstoffe. Ill. Landw. Zeitung, 30 Jahrgangen, Heft 95, Seite 871-881. 1910.

one of each being fertilized and one unfertilized. The lysimeters were 1.2 meters deep and contained 4 cubic meters of soil. The drainage water was caught and analyzed for four years. The first year there was no crop, the second year potatoes were grown, the third oats, and the fourth rye. The following results were shown:—

AVERAGE COMPOSITION OF DRAINAGE WATER IN PARTS PER MILLION

SOIL	TREATMENT	TOTAL NITROGEN	NITRATE NITROGEN	ORGANIC NITROGEN	K_2O	CaO
Moor soil	Fertilized	32.7	30.0	2.7	32.2	405
	Untreated	65.0	60.3	4.7	26.2	307
Loamy sand low in humus	Fertilized	25.5	25.1	0.4	25.1	93
	Untreated	20.9	20.4	0.5	8.5	90
Sandy loam high in humus	Fertilized	67.8	64.6	3.1	70.2	391
	Untreated	69.5	66.1	3.4	47.4	414

Absorption will not proceed to an unlimited extent. A soil will cease to absorb any particular substance after a certain quantity has been taken up. This quantity will vary with every soil. Clay and loam soils have greater absorptive power than sandy soils. This difference, both as to amount and as to rate of absorption, is well shown by the following curves adapted from Schreiner and Failyer.[1]

[1] Schreiner, O., and Failyer, G. H. The Absorption of Phosphates and Potassium by Soils. U. S. D. A., Bur. Soils, Bul. 32. 1906. See also Cameron, F. K., and Bell, J. M. The Mineral Constituents of the Soil Solution. U. S. D. A., Bur. Soils, Bul. 30, pp. 42–66. 1905. Patten, H. E., and Waggaman, W. H. Absorption by Soils. U. S. D. A., Bur. Soils, Bul. 52. 1908.

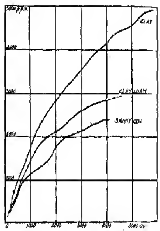

FIG. 55.—Curves showing the absorption of PO_4 in parts to a million by various soils from a solution of monocalcium phosphate, containing 200 parts to a million of PO_4. The volume of the percolate is used as the abscissas.

Note.—The law which appears to govern absorption of phosphates and potash by the soil may be expressed mathematically as follows:—

$$\frac{dy}{dv} = K(A - y)$$

in which K is a constant, A the maximum quantity possible for the soil to absorb, and y the quantity actually fixed when v, volume of the solution, has percolated through.

A short discussion of the mathematics of this law may be found in the following publication: Schreiner, O., and Failyer, G. H. The Absorption of Phosphates and Potassium by Soils. U. S. D. A., Bur. Soils, Bul. 32, pp. 21–24, 37–39. 1906.

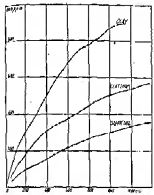

Fig. 95.—Curves showing the absorption of K in parts to a million by various soils from a solution containing 200 parts to a million of K. The volume of the percolate is used as the abscissas.

262. **Time required for absorption.** The amount of absorption depends on the time of contact between the soil and the solution. While a large part of the dissolved base is taken up in a short time after being placed in contact with the soil, the maximum absorption is effected only after a considerable period. Ammonia, according to Way, reaches its maximum absorption in half an hour; while Henneberg and Stohmann[1] found that phosphorus required twenty-four hours to reach the same degree of absorption.

[1] Henneberg, W., and Stohmann, F. Ueber das Verhalten der Ackererde gegen Lösungen von Ammoniak und Ammoniaksalzen. Jour. f. Landw., Neue Folge, Band 3 (Der ganzen Reihe siebenter Jahrgang), Seite 25–47. 1859.

This, however, has no significance so far as danger from loss of a soluble fertilizer constituent is concerned, since water, even after a heavy rain, would not pass so quickly through the soil that absorption would not take place, except possibly in the case of soil of a very coarse texture. The depth through which the substance is distributed in the soil may, however, be influenced by the time required for its absorption. Ordinarily fertilizers do not penetrate very far into the soil. Demolon and Brouet[1] have investigated the rate and distance of penetration of certain soluble salts in soils, and find that a total rainfall of ten inches is not sufficient to carry down sodium nitrate in a sandy soil to a depth of eight inches.

253. Insolubility of certain absorbed substances. Although bases once absorbed may be easily displaced by other bases, it is difficult to dissolve them from the soil with pure water. Peters[2] treated 100 grams of soil with 250 cubic centimeters of water containing potassium chloride, of which 0.2114 gram of K_2O was absorbed. The soil was then leached with distilled water, using 125 cubic centimeters of water daily for ten days. At the end of that time 0.0875 gram of K_2O had been removed, or at the rate of 28,100 parts of water to one part of K_2O dissolved from the soil. Henneberg and Stohmann[3] found that it required 10,000 parts of water

[1] Demolon, A., and Brouet, G. Sur la Pénétration des Engrais Solubles dans les Sols. Ann. Agron., Tome 28, pp. 401-418. 1911.

[2] Peters, E. Ueber die Absorption von Kali durch Ackererde. Landw. Vers. Stat., Band 3, Seite 113-151. 1860.

[3] Henneberg, W., and Stohmann, F. Ueber das Verhalten der Ackererde gegen Losungen von Ammoniak und Ammoniaksalzen. Jour. f. Landw., Neue Folge, Band 3 (Der ganze Reihe siebenter Jahrgang), Seite 35-47. 1859.

to dissolve one part of absorbed ammonia from the soil.

254. Influence of size of particles. — The surface area of the soil particles determines to some extent the amount of substance absorbed. For this and other reasons, a fine-grained soil absorbs a greater quantity of material than a coarse-grained soil. In fact, it was early shown by Way[1] that the phenomenon of absorption is largely a function of the silt, clay, and humus of the soil.

255. Causes of absorption. — A number of causes have been assigned for the absorption of substances by soils, and there can be no doubt that the phenomenon is not due to any one process. Several distinct causes are now very generally recognized, while others that have been suggested may have a part in the result.

256. Zeolites. — As the result of his extended researches on absorption of soils, Way concluded that the property of absorption, or fixation of bases, rests largely with the hydrated silicates of aluminium, containing calcium or magnesium and one of the alkali metals, these compounds being known as zeolites. He prepared artificially a hydrated silicate of aluminium and sodium, and found that by treating this with a solution of a calcium salt he could replace most of the sodium, obtaining thereby a silicate of aluminium, calcium, and part of the sodium that was originally contained in the silicate. The remainder of the sodium could be replaced by potassium from solution and, likewise, by magnesium and ammonium.

[1] Way, J. T. On the Power of Soils to Absorb Manure. Jour. Royal Agr. Soc. England, Vol. 11, pp. 313–379. 1850. Also, On the Power of Soils to Absorb Manure. Jour. Royal Agr. Soc. England, Vol. 13, pp. 123–143. 1852. Also, On the Influence of Lime on the "Absorptive Properties" of Soils. Jour. Royal Agr. Soc. England, Vol. 15, pp. 491–515. 1854.

Way found further that exposure to a strong heat destroyed the absorptive properties of these substances, as did also treatment with strong hydrochloric acid. In all these respects the absorptive properties of the soil and of the zeolites coincide.

267. Chabazite. — Eichhorn[1] experimented with the natural zeolite chabazite, and found that he could produce substitutions by means of the proper salt solutions. In column I of the table below is given the composition of chabazite used for the experiment; in column II is stated its composition after treatment with a solution of sodium chloride; and in column III the composition after the zeolite is further treated with a solution of ammonium chloride: —

COMPOSITION OF CHABAZITE ORIGINALLY AND AFTER TREATMENT WITH SODIUM CHLORIDE AND AFTERWARDS WITH AMMONIUM CHLORIDE

CHANGE	I	II	III
SiO_2	47.4	48.3	51.3
Al_2O_3	20.7	21.0	22.2
CaO	10.4	6.7	4.2
K_2O	0.7	0.6	0.6
Na_2O	0.4	5.4	
H_2O	20.2	18.3	14.9
$(NH_4)_2O$	0.0	0.0	6.9

The substitutions were evidently made at the expense of calcium in the compound, both when treated with sodium and when treated with ammonium salts in chemically equivalent quantities. These and subsequent ex-

[1] Eichhorn, H. Ueber die Einwirkung Verdünnter Salzlösungen auf Ackererde. Landw. Centrlb. f. Deutschland, 6 Jahrgang, Band 2, Seite 169–175. 1858.

periments by numerous investigators have been rather widely accepted as indicating that the zeolites are at least partly responsible for the absorptive properties of soils. It has been shown further that the absorptive power of a soil is more or less proportional to the quantities of acid-soluble silicates it contains. The zeolites being rather easily soluble in strong mineral acids, it is held that the bases so combined are more readily available to plants than in most combinations found in the soil, and yet are not easily leached out of it.

258. Presence of zeolites questioned. On the other hand, zeolites have never been definitely proved to be present in soils. Merrill[1] has attempted to show that they cannot be of wide occurrence in soils, but neither their absence nor their presence has been demonstrated. Since the time when Way first published his researches in 1850, the zeolite constituents of the soil have generally been held to be largely responsible for its absorptive power for bases.

259. Absorption of phosphoric acid. — It has already been said that although hydrochloric, sulfuric, and nitric acids are not absorbed by soils, except in small quantities, phosphoric acid is absorbed and retained in an almost insoluble condition so far as extraction with water is concerned. That this absorption cannot be due to zeolites is generally conceded, and has recently been demonstrated, for permutite at least, by Rostworowski and Wiegner,[2] who in a carefully conducted experiment

[1] Merrill, G. P. Rocks, Rock Weathering, and Soils, pp. 362-367. New York. 1906.

[2] Rostworowski, S., and Wiegner, G. Die Absorption der Phosphorsäure durch "Zeolithe" Permutite. Jour. f. Landw. Band 60, Seite 223-235. 1912.

with this zeolite — which is an amorphous gel containing potassium, calcium, aluminium and silicic acid — found that there was no absorption of phosphoric acid from a neutralized solution of monocalcium phosphate or from a solution of dicalcium phosphate at various degrees of concentration.

360. **Formation of insoluble phosphates.** — The retention of soluble phosphoric acid in soils may be easily accounted for by the fact that there are present in all soils hydrated ferric oxide and hydrated silicates of alumina, and frequently calcium carbonate, with which substances phosphoric acid in solution would naturally form compounds insoluble in water. Iron and aluminium phosphates are practically insoluble in water containing carbon dioxide or weak organic acids such as might be present in soil water. Calcium carbonate forms with a soluble phosphate fertilizer some dicalcium phosphate, the solubility of which in soil water is much greater than the iron and aluminium phosphates. This is one of the advantages of keeping a soil well supplied with lime if a superphosphate fertilizer is to be used. Even the tricalcic phosphate, although less soluble than the dicalcic, is more readily soluble than the iron and aluminium phosphates. As lime has a tendency to move downward in soil, and as phosphoric acid is retained in the plowed depth when added as a fertilizer, it is important that the applications of lime be sufficiently frequent to keep this part of the soil in a condition to form the lime phosphates.

Cameron[1] has suggested that the absorption of phosphoric acid is probably due to the formation with lime or ferric oxide of a solid solution, which might account

[1] Cameron, F. K. The Soil Solution, p. 58. Easton, Pennsylvania. 1911.

for the availability of phosphorus in soils to which a superphosphate fertilizer had been applied many months previously. It might explain also the availability of a superphosphate on soils devoid of calcium carbonate. Although such availability is always less than where this carbonate exists, it is greater than would be accounted for by the solubility of ordinary iron phosphate.

261. **Adsorption.** — There is a physical fixation, termed adsorption, due to the concentration of the soil solution in immediate contact with the surface of the particles. The phenomenon is familiarly exemplified in the clarifying effect of the charcoal filter. This process results in the retention, in fine-grained soils, of considerable soluble material that would otherwise be washed out. In the case of nitrates, which are not retained by the zeolites, adsorption is an important factor (par. 215). If a solution of a known quantity of nitrate of soda is added to a clay soil, and an attempt is then made to extract the nitrate from the soil with distilled water, it will be found impossible to recover a very appreciable proportion of the amount added. While adsorption probably does not account for all the nitrates retained, there can be no doubt that it plays an important part. Nutritive salts held in this way are readily available to the plant, where root hairs come in contact with the soil particles. It is not impossible that other fertilizer constituents are held by the soil in this manner.

262. **Absorption by colloids.** — According to Van Bemmelen,[1] who has made a very exhaustive study of this

[1] Van Bemmelen, J. M. Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde. Landw. Vers. Stat., Band 35, Seite 69-180. 1888. Also, Die Absorption, Seite 548. Dresden, 1910.

subject, absorption by soils is, without doubt, largely due to the presence of colloidal matter which exerts an absorbent action for water, gases, solutes, and solids in suspension. The colloidal matters in soils that contribute to their absorptive properties are the following: —

(1) remains of plant and animal tissues;
(2) humous substances;
(3) colloidal iron oxide;
(4) colloidal silicic acid;
(5) amorphous colloidal silicates that have been formed through weathering.

Van Bemmelen also credits crystalline silicates with absorbent properties, although he does not consider that their action is very important. Absorption is brought about also by true chemical combination of soil compounds with substances in solution, by which certain of the cations or anions in solution are chemically combined and remain in the soil in a very difficultly soluble condition.

263. Absorptive properties of colloidal matter. — Among the products of rock weathering there have been found in soils amorphous substances that are of the nature of colloidal gels. These, with the other colloidal matter, are contained in the very small particles that remain for a long time in suspension when soil is stirred up in water. These colloids are coagulated by many acids, and by some bases and salts. This is especially true of the material that is dialyzable. Some of these again go into solution on being treated with water, while others remain insoluble until they undergo molecular change. Many colloids form hydrogels with soil water. These hydrogels are not ordinary chemical compounds. Gels dry very slowly. They adsorb water in varying quantities, and

in certain definite proportion as do crystalloids in the process of crystallization. The more water adsorbed by colloids, the less firmly is it held in combination. Therefore it is easier to evaporate the water when a large quantity has been taken up, and as the amount decreases it becomes more difficult to drive it off.

Another property of colloidal matter is that when it is separated from solution it carries down with it other substances in the solution from which it is precipitated. If, on the other hand, the colloidal matter has been precipitated in a pure state, it absorbs substances from solutions with which it remains in contact for some time. The substances taken up in this way are not chemically combined, but substances that unite chemically may be absorbed.

The combinations produced by absorption are weak and it is possible to leach out the combined substances, which are generally held in the water of the gels. The following example of one kind of absorption is given by Van Bemmelen:[1] ten grams of a hydrogel having the composition $SiO_2 . 4.2 H_2O$, shaken with 100 cubic centimeter solution of 20 molecular equivalent KCl, will absorb 0.8 to 1.1 molecular equivalent of the dissolved substance. The absorption in this case was as if the solution had been diluted with 4.2 to 5.8 cubic centimeters of water. As the amount of gel water in 10 grams of hydrogel of SiO_2 is about 5 cubic centimeters, the assumption may be made that the dissolved substance is taken up in equal concentration by the gel water. Ten grams of hydrogel of SiO_2 shaken with 100 cubic centi-

[1] Van Bemmelen, J. M. Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde. Landw. Vers. Stat., Band 35, Seite 76. 1888.

meter solution of 50 molecular equivalent KCl — that is, $2\frac{1}{2}$ times the concentration of the former solution — absorbs $2\frac{1}{2}$ times as much, or 2.1 to 3.5 molecular equivalent. This applies also to concentrations five times stronger than the first mentioned above, but beyond that the relation is not so simple. It serves, however, to illustrate the manner in which the absorption takes place from dilute solutions.

264. Selective absorption. — A selective absorption is very common, especially from solutions of salts having weak acids, a greater fixation of the bases taking place than of the acids. Dissociation of the salts takes place in the solution, the bases being absorbed, in consequence of which further dissociation occurs; and this proceeds until an equilibrium is established between the absorbing and combining power of the colloidal material and the reverse action of the water and resulting acids. In this way the absorptive power decreases as the amount absorbed becomes greater.

The colloidal silicates possess the property of absorbing a certain base when presented to it in solution, and contributing in return a chemically equivalent quantity of some other base. Potassium is most firmly combined in the soil and most strongly withdrawn from solution, with an exchange of a chemically equivalent quantity of calcium, sodium, and magnesium, which passes into the solution. If a soil is treated with a solution of potassium, magnesium, sodium, or calcium salts of equal concentration, the concentration of the solution in the end is less for the potassium than for the magnesium, and less for the magnesium than for the sodium and the calcium, because the potassium is most strongly bound in the colloidal material, while the calcium and sodium are least

ns. In other words, the action of a calcium salt in solution on the absorbed potassium combination is less than the action of a dissolved potassium salt on the absorbed calcium combination. Thus it comes about that under similar conditions of temperature, volume, and concentration of the solution, the quantity of calcium or of sodium or of magnesium that goes into solution when colloidal silicates are treated with a solution of a potassium salt is greater than the quantity of potassium that would go into solution if the same silicates were treated with a solution containing the salts of any of these other bases.

265. Absorptive power of colloidal silicates. — The quantity of a substance that a certain weight of a colloidal silicate can absorb increases with the strength of the solution of the substance presented for absorption, because the final solution can remain stronger and consequently its solvent power for that particular substance is less. The point of equilibrium between the fixing power of the colloid and the solvent action of the solvent therefore varies with the strength of the solution.

The nature of the acid with which a base is combined likewise has an influence on the quantity of the base absorbed. A base combined with a weak acid is absorbed in greater amount than the same base combined with a strong acid. This is presumably because the stronger acid remaining in solution has a greater solvent action.

266. Absorption by colloids *versus* absorption by zeolites. — The early conception of the phenomenon of fixation in soils was naturally a chemical one and was founded on the chemical knowledge of that day. The fact that the substitution of bases in the solutions passed through the soil was in chemically equivalent quantities,

placed it in line with what was known regarding chemical reactions. Zeolites were found to possess absorbent properties of a similar nature toward salts in solution, a characteristic of which is the substitution of bases and the appearance in solution of the released base in combination with the acid of the original salt. It was a natural conclusion that true mineral zeolites exist in soil and that the absorptive properties of soil are due to their action.

Many years later, when the principles of physical chemistry had been applied to the study of colloids, it was shown that absorptive properties are possessed by certain colloids similar to those characteristic of soils. Zeolites have never actually been isolated from any soil. This fact has always occasioned some doubt as to the hypothesis to which their properties have given rise. Colloids, on the other hand, are well known to occur in soils, but the exact nature of soil colloidal matter is not well understood; consequently there is considerable indefiniteness about the extent of their absorptive function, and even Van Bemmelen grants the crystalloids a part in this phenomenon.

The zeolite hypothesis furnished an explanation for the form in which the available plant-food materials of the soil are held. On it is largely based the idea that the solution of a soil in strong hydrochloric acid represents the nutrients that are available to plants. The silicates that go into solution are held to be the zeolitic silicic acid and the bases with which it is united. The fact that such treatment largely destroys the absorptive properties of a soil is taken as a proof of this. It would, however, answer equally well as an argument in favor of colloidal absorption, as the colloidal condition of the

silicates would be destroyed by the same treatment. On the whole, the evidence appears to be in favor of the dominance of colloidal absorption rather than crystalloidal absorption by soils, with its important function in conserving soluble fertilizers and retaining a supply of plant nutrients in a more or less readily available condition.

287. **Absorption by organic matter.** — The partially decomposed organic matter in soils, especially that part which has undergone such transformations as to form humus (par. 90), has an absorptive power. Soils rich in humus, without doubt, owe much of their fertility to the retention by that constituent of a large supply of readily available plant-food material. Many prairie soils that have been reduced in productiveness under cultivation respond to the application of organic matter in a remarkable manner. Humus in these soils seems to be the chief conserver of readily available plant-food materials.

Van Bemmelen,[1] who has studied these compounds, states that soils hold colloidal humous compounds containing ammonia, potassium, sodium, and other substances, as well as iron oxide. A part is soluble, or forms soluble compounds with alkalies, but the principal part is insoluble. Some of these latter compounds are of a colloidal nature and of changing composition. The soluble matter is easily precipitated by a salt solution and carries down with it bases from the solution. Absorption of bases also takes place from solution, with substitution of one base for another. Potassium is more strongly held in combination than is calcium or magnesium. Bases are removed, however, only from salts of the weaker acids.

[1] Van Bemmelen, J. M. Die Absorption, Seite 135-141. Dresden, 1910.

268. Absorption of water vapor and of gases by soils. — Hygroscopic water in soils has already been discussed (pars. 133, 134, 135). It need merely be remarked here that there is a close relation between the absorptive power of a soil for water vapor and for bases. Soils having a high content of humus and composed of very fine material are likely to have great absorptive properties for both vapors and solutes.

In a similar way soils absorb gases. The deodorizing property of soil is well known. Decomposing organic matter is rendered inoffensive by covering it with soil. Gases produced in the processes of decomposition are largely absorbed by the soil. The fertility of the soil may be increased by the absorption of certain gases.

269. Absorption of ammonia. — Ammonia, which exists in minute quantities in the air, is absorbed by soils, and also when given off by decomposing organic matter in the soil. As all nitrogenous organic matter may eventually form ammonia when decomposed, the ability of the soil to absorb it is very important. Quartz alone will absorb only a very small quantity of ammonia, while a clay soil will hold practically all that is likely to be produced by the decomposition of the organic matter incorporated in it.

270. Absorption of carbon dioxide. — Carbon dioxide is absorbed by soils to a very considerable extent, and this also adds to the productiveness of soils, since it aids in their decomposition. The supply of carbon dioxide comes from decomposing organic matter and from plant roots. As will be explained later, the soil air always contains a considerable supply of this gas, and its condensation and absorption is constantly going on. It forms soluble bicarbonates with the alkalies and bases of soils, producing a readily available plant-food material.

271. Absorption of nitrogen and oxygen. – Nitrogen is absorbed by soils to a greater degree than is oxygen. The latter probably is of greater importance to soil fertility, as its absorption is accompanied by oxidation of other absorbed gases. Because of their absorptive properties and their great surface area, soils have strong oxidizing power.

The absorption of gases by soils is largely an absorption phenomenon, the gases being condensed on the surface of the particles. Von Dobeneck[1] has shown that the absorption is greater, the finer the particles of soil, but this increase is not directly proportional to the increase in surface, large particles apparently having a greater adsorptive power than their surface area would indicate.

272. Relation of temperature to gas absorption. The temperature of the soil influences its absorptive properties for vapors. As the temperature increases the absorption becomes less. Hilgard[2] does not find this to be the case (par. 130). He exposed soils to a moisture-saturated atmosphere and found that they absorbed more moisture at high than at low temperatures. In his conclusions, however, he is doubtless in error. All the work previous to his gave a directly contrary result, and a more recent investigation by Patten and Gallagher[3] confirmed the work of the earlier investigators.

[1] Von Dobeneck, A. F. Untersuchungen über das Adsorptionsvermögen und die Hygroskopizität der Bodenkonstituenten. Forsch. a. d. Agri.-Physik, Band 15, Seite 163–228. 1892.

[2] Hilgard, E. W. Soils, pp. 190–198. New York, 1906.

[3] Patten, H. E., and Gallagher, F. E. Absorption of Gases and Vapors by Soils. U. S. D. A., Bur. Soils, Bul. 51, pp. 31–85. 1908.

273. Relation of absorptive capacity to productiveness. — The absorptive capacity of a soil is not so much a measure of its immediate as of its permanent productiveness. It is well known that a very sandy soil responds quickly to the application of soluble manures, but that the effect is confined mainly to one season; while a clay soil, although not so quickly responsive to fertilization, shows the effect of the application much more markedly the second or the third year than does the sandy soil. Adsorption, which is largely shown in sandy soil, holds the nutritive material in a very readily available condition, while absorption by amorphous compounds renders these substances somewhat less readily available. There are also other reasons why the sandy soil is more responsive. King,[1] in working with eight types of soil from different parts of the United States, found that those soils removing the most potassium from solution gave the largest yield of crops. It would not be permissible, however, to adopt this test as a method for determining productiveness in soil.

274. Absorption as related to drainage. — The drainage water from cultivated fields in humid regions, and to a less extent in semiarid and arid regions, except where irrigation is practiced, carries off very considerable quantities of plant-food material. The loss of this material is due to the operation of the various natural disintegrating agents on the soil mass, and to the application of fertilizing materials in a soluble form. The various absorptive properties stand between the natural solubility of the soil and the tendency to loss in drainage, and hold, in a condition

[1] King, F. H. Influence of Farm Yard Manure upon Yield and upon the Water-Soluble Salts of Soils, p. 26. Madison, Wisconsin. 1904.

in which they may readily be used by the plant, these materials which would otherwise be lost.

275. Substances usually carried in drainage water. — However, some material is always lost in drainage water, of which, among the bases of the soil, those most likely to be found are calcium, sodium, magnesium, and potassium; and of the acids, carbonic, nitric, sulfuric, and hydrochloric. Nitric acid and lime undergo the most serious losses. The former may be curtailed to a great extent by keeping crops growing on the soil during all the time that nitrification is going on, and if the crop does not mature, or if for any other reason it is not desired to harvest the crop, it should be plowed under, to return the nitrogen in the form of organic matter. A crop used for this purpose is called a **catch crop**. Rye is used rather commonly as a catch crop, as it continues growth until late in the fall and resumes growth early in the spring, conserving nitrates whenever nitrification is likely to occur, and it may then be plowed under to prepare the land for another crop. Rye also has the advantage of small cost for seed.

The loss of calcium cannot well be prevented, and the use of commercial fertilizers always greatly increases such loss. The only remedy is the application of some form of calcium to the soil.

276. Drainage records at Rothamsted. — Drainage water from a series of plots at the Rothamsted Experiment Station, which have been manured in various ways and planted to wheat each year since 1852, have been analyzed at certain times, and the results of these analyses, as compiled by Hall,[1] give some idea of the loss

[1] Hall, A. D. The Book of the Rothamsted Experiments, pp. 237-239. New York, 1905.

of salts from cultivated soils. The drainage water was obtained from the tile drains, a line of which extended under each plat from one end to the other and opened into a ditch, so that the water could be collected when desired. The analyses are shown in the table on page 371.

Ammoniacal nitrogen in the drainage water is very small in quantity, but nitrate nitrogen is present in quantities sufficient to make the loss of some concern. The use of sodium nitrate occasioned the greatest loss of nitrogen, while ammonium salts and farm manure contributed nearly as much. From forty to fifty pounds of nitrogen to the acre may be lost annually in this way; this amount would have a commercial value of eight or nine dollars.

277. Drainage records at Bromberg.—It is not always the case that a manured soil loses more fertilizing material than an unfertilized one. Gerlach[1] reports experiments in soil tanks at the Bromberg Institute of Agriculture, as the result of which five soils, when rationally fertilized, yielded larger crops and lost in the main less nitrogen and lime in the drainage water than the same soils unmanured. The loss of potash was slightly greater from the manured than from the unmanured soils. Apparently the stimulation that the plants received from the fertilizer enabled them to make such a good growth that they absorbed more soluble nitrogen and lime in excess of the unfertilized plants than was added in the fertilizer, and nearly as much potash.

[1] Gerlach, M. Ueber die durch Sickerwasser dem Boden Entzogenen Menge Wasser und Nährstoffe. Illus. Landw. Zeitung, 30 Jahrgang, Heft 85, Seite 871–881. 1910. Also, Untersuchungen über die Menge und Zusammensetzung der Sickerwasser. Mitt. K. W. Inst. f. Landw. in Bromberg, Band 3, Seite 351–381. 1910.

COMPOSITION OF DRAINAGE WATER FROM BROADBALK WHEAT PLOTS, ROTHAMSTED EXPERIMENT STATION

MANURES APPLIED, RATE TO THE ACRE	Parts per Million											Average Yield of Wheat, 1852–1880
	Peroxide of Iron	Lime	Magnesia	Potash	Soda	Chlorine	Sulfuric Acid	Phosphoric Acid	Soluble Silica	Nitrogen as Ammonia	Nitrogen as Nitric Acid	
Plot												Bus.
2 Farm manure 14 tons	2.8	147.4	4.9	3.4	13.7	20.7	158.3	—	88.7	0.19	10.1	38.7
3 and 4 No manure	3.7	92.1	6.1	1.7	6.9	10.7	54.7	0.68	15.9	0.12	3.0	13.1[1]
5 Minerals only	4.4	124.5	5.4	3.4	11.7	11.1	66.2	0.51	15.4	0.13	3.1	14.9
6 Minerals + 200 pounds ammonium salts	2.7	143.9	7.9	4.4	10.7	20.7	73.2	1.08	22.7	0.29	5.0	25.0
7 Minerals + 400 pounds ammonium salts	3.1	151.4	8.3	2.9	10.0	26.1	90.1	0.92	17.0	0.07	14.0	32.0
8 Minerals + 600 pounds ammonium salts	2.7	197.3	8.9	2.7	10.5	39.4	99.7	0.77	20.9	0.27	19.9	37.1
9 Minerals + 550 pounds nitrate of soda	5.1	136.1	3.3	4.1	68.1	12.0	41.0	—	10.9	0.14	13.4	
10 400 pounds ammonium salts alone	4.0	164.1	7.4	1.0	7.6	32.5	34.4	1.49	13.7	0.08	13.0	20.7
11 400 pounds ammonium salts + superphosphate	3.4	165.5	7.3	1.0	6.9	33.9	64.2	1.55	11.8	0.17	14.5	24.0
12 400 pounds ammonium salts + superphosphate + sulphate soda	3.3	191.8	6.6	2.7	24.6	30.9	96.7	1.50	17.0	0.30	15.1	30.0
13 400 pounds ammonium salts + superphosphate + sulphate potash	3.7	201.4	9.6	8.8	6.1	30.9	89.6	1.60	25.3	0.19	17.4	31.5
14 400 pounds ammonium salts + superphosphate + sulphate magnesia	3.7	257.7	13.0	3.0	9.5	38.4	99.7	1.01	16.0	0.30	15.9	30.1
16 Minerals + 1,100 pounds nitrate of soda	4.9	137.1	3.2	2.4	91.1	11.4	31.9	0.91	17.0	0.09	7.0	—

[1] Yield of Plot 3 alone.

278. Losses of nitrogen and calcium. — The most serious losses of plant nutrients in the drainage water of soils are those of nitrogen and calcium, and both are to an extent unavoidable. Potassium and phosphorus, which must also be purchased in manures, are lost only at the rate of a few pounds to the acre. Nitrogen and calcium may be conserved by maintaining a crop on the soil continually. A large removal of nitrogen in the drainage water is usually accompanied by a large removal of calcium; for nitrogen is leached from the soil mainly in the form of nitric acid, which of course combines with a base, and calcium being the base finally liberated it is carried off in drainage water. While most of the calcium in drainage water is in the form of bicarbonate, the quantity is greatly increased by nitric acid.

The relation of nitric acid to calcium in drainage water is shown by experiments with soil in large tanks from which drainage water was collected. Plants were grown in the soil of certain tanks, while others had none, other conditions being similar. Analyses of the drainage water at Ithaca, New York, as reported by Lyon and Bizzell[1] show a greatly increased loss of calcium from the unplanted tanks, from which the loss of nitrate nitrogen was also much greater:

NITROGEN AND CALCIUM REMOVED IN DRAINAGE-WATER BETWEEN MAY 23, 1910, AND MAY 1, 1911. CALCULATED TO POUNDS TO THE ACRE

CROP GROWN	NITRATE NITROGEN	CALCIUM
None	119.6	406.7
Maize	10.8	188.0
Oats	12.5	173.4

[1] Lyon, T. L., and Bizzell, J. A. Composition of the Drainage Water of a Soil with and without Vegetation. Jour. Indus. and Eng. Chem., Vol. 3, pp. 742–743. 1911.

Where crops were present to absorb the nitric acid, calcium was greatly conserved. The quantities of material carried off in drainage water was doubtless abnormally high in this case, as the soil had recently been placed in the tanks.

279. Composition of surface water. — Another method proposed for obtaining these data is to analyze and measure the water draining from a known area of land. Norton[1] has done this in the valley of Richland Creek, Arkansas, and has calculated the loss of a number of the soil constituents. A comparison of the figures obtained by Norton with those obtained by Lyon and Bizzell in the experiments just quoted will give some idea of the quantities of mineral matter removed from soils by drainage water. The Arkansas soil had presumably received little manure. The soil in the Cornell University tanks had previously received fifteen tons of stable manure. The Arkansas drainage doubtless included some surface water that had never passed through the soil and was therefore poor in mineral matter; the large quantity of volatile matter indicates its surface nature, as water that passes through a soil contains little organic matter.

There is little similarity in the results of these analyses. They serve, however, to bring out the differences between the composition of the run-off and the drainage water of soils, in so far as that may be judged from widely different soils and climatic conditions, including the rainfall.

[1] Norton, J. H. Quantity and Composition of Drainage Water and a Comparison of Temperature, Evaporation, and Rainfall. Journal Am. Chem. Soc., Vol. 30, pp. 1186–1190. 1908.

SUBSTANCES REMOVED IN DRAINAGE WATER FROM ONE ACRE OF LAND. POUNDS IN ONE YEAR

	Arkansas	Lyon and Bizzell	
		Planted Soil	Bare Soil
Total solids	704.0	800	2584
Organic matter	134.0	6	0
Nitrogen	4.0	11	119
Potash	5.0	.6	11
Phosphoric acid	0.1	Trace	Trace
Lime	83.0	158	402

It will be seen that the total solids in the drainage water from the Arkansas land and from the planted tank were not greatly different in amount, but that some of the constituents differed greatly. This was notably the case with organic matter and with lime. The former was doubtless carried largely in the run-off and not in the leachings. The latter was probably more abundant in the glaciated soil used in the tank than in the residual soil of Arkansas.

CHAPTER XVII

ACID, OR SOUR, SOILS

Some soils are known as acid, or sour, soils. The property of acidity is of practical significance because some plants do not grow so well on sour soils as they do on soils that are neutral or alkaline; on the other hand, some crops prefer an acid soil. Sour soils are rarely met with in arid regions, but in humid sections of the United States they are commonly found.

280. Nature of soil acidity.—Soils may be acid, or sour, so far as their relation to plant growth is concerned, (1) when free acids are present, (2) when no soluble free acid exists, but when there is a deficiency of basic material in the soil. Decomposition of organic matter in certain soils under an inadequate supply of oxygen often results in the formation of considerable quantities of organic acids, as has already been explained (par. 33).

281. Positive acidity.—The formation of organic acids under conditions of insufficient oxygen supply is frequently seen in muck and other soils high in organic matter that are saturated with water and that are also deficient in lime. In such cases an acid condition is very likely to be found, but when the land is drained the acidity usually disappears because of the better aëration resulting. When a large quantity of green vegetation is plowed under, as is done in green-manuring land, a sour condition sometimes appears after the material has

had time partially to decay. The acidity of soil that arises from the presence of free acids has been termed positive acidity.

It is to be presumed that soils in which free acids exist are rather deficient in basic material, and that the bases are held so firmly combined that some of the relatively weak organic acid present is not capable of forming salts with them. Plummer[1] has shown that dihydroxystearic acid when added to an acid soil had a distinctly toxic effect on wheat plants, but when added to the same soil previously treated with lime there was no toxic effect, indicating that this substance retained its acid properties in the unlimed soil.

282. Negative acidity. A soil deficient in basic material but containing no soluble free acids may be sour as regards its relation to plant growth. At least such a soil may be greatly benefited by liming, although it shows no acidity to most of the ordinary indicators of acidity when these are used in the customary way. This condition has been termed negative acidity and is really not acidity according to a correct use of the word. Such acidity does not have a direct effect on the plant, but an indirect one arising from a lack of bases. Soils that are acid in this sense always have a large capacity for absorbing lime or other bases, before exhibiting an alkaline reaction. Calcium being, as has already been seen (par. 264), the base most liberally released to solution, there is a tendency toward the formation of calcium carbonate in any soil dependent on the equilibrium be-

[1] Plummer, J. K. The Isolation of Dihydroxystearic Acid from Volusia Silt Loam. Thesis presented in partial fulfillment of the requirements for the degree of Master of Science. Cornell University Library (not published). 1911.

tween the basic material and the absorptive substances in the soil. Thus, a soil containing large quantities of clay, and other absorbent substances requires more basic material for the formation of calcium carbonate than does a soil having less absorptive material. Furthermore, with the same original content of basic material, the former soil requires a greater addition of lime to overcome its sourness than does the latter. For this reason a heavy soil usually requires a larger dressing of lime to correct its acidity than does a light one.

Even if a soil does not have its absorptive capacity for bases satisfied, there is some formation of calcium carbonate constantly taking place, as is evidenced by the removal of the bicarbonate of calcium in the drainage water of soils that are distinctly acid. The benefits that soils derive from the presence of calcium carbonate will be mentioned later (para. 464-467). It need only be said here that its presence in insufficient quantity constitutes a form of so-called acidity, or sourness, in soils. The formation of calcium carbonate in a given soil increases with the mass of base.[1] The effect of an application of lime, therefore, is to increase the quantity of carbonate formed, even when the absorptive capacity of the soil is not satisfied. This is why even relatively small applications of lime are beneficial to soils having great absorptive capacity.

383. **Production of sour soils.** — Soils in a humid region tend to become acid. This may be due to any one or more of several causes: (1) removal of calcium and other bases in drainage water; (2) removal of bases by plants; (3) formation of salts of the bases with organic matter incorporated with soil; (4) accumulation of acid residues of fertilizers.

284. Removal of bases by drainage as a cause for acidity. — The most potent cause of acid soils is doubtless the removal of bases in drainage water. The quantities of basic material that may be lost from an acre of soil are shown elsewhere (pars. 278, 279). These bases are removed largely as bicarbonates, being obtained from the hydrated aluminium silicates and other colloidal matter. When the soil is uncropped a considerable loss of lime occurs in the form of nitrate. As the decomposition of the organic matter of the soil always results in the formation of carbon dioxide and nitric acid, and as decomposition is continually going on except when the temperature of the soil becomes too low to admit of it, the drain of bases from the soil is almost continuous. Formation of carbon dioxide and of nitric acid occurs largely in the surface soil; consequently the removal of bases begins there. The result is that soils are likely to contain less calcium in the surface layers than at lower depths. Ames and Gaither[1] have shown from a large number of analyses of Ohio soils that those containing calcium carbonate in appreciable quantities have more calcium in the subsoil than in the surface six inches. In other soils this was not uniformly the case. Leaching is, of course, greater in amount where considerable quantities of calcium carbonate are present than where it is lacking.

285. Removal of bases by plants. — Plants always remove more bases than acids from soils in the process of their growth. The table in paragraph 339 showing the composition of the ash of some crops indicates that the calcium, potassium, and magnesium removed from

[1] Ames, J. W., and Gaither, E. W. Soil Investigations. Ohio Agr. Exp. Sta., Bul. 261. 1913.

the soil in this way is very considerable. When the vegetation on the land is returned to it after life ceases and its organic material is again incorporated with the soil, there is no loss in this way, but in ordinary agricultural practices most of the above-ground portion of the crops is removed from the land. The manure of growing animals returns to the soil only a small proportion of the calcium that was originally in the plants.

Breazeale and LeClerc[1] found that the selective action of plants in absorbing more bases than acids from a nutrient solution caused the solution to become toxic to wheat seedlings because of its acidity.

286. **Effect of green manures on acidity.** — Although the return of vegetation to the land on which it grew does not result in any actual loss of basic material to the soil, it generally results in the formation and liberation of organic acids that unite with the basic material and thus render it neutral. In soils deficient in lime the incorporation of green-manure crops has been considered to temporarily produce an acid condition. Coville[2] determined the acidity of some green-manure crops, on the basis of which he has estimated the acidity, in terms of ground limestone required to neutralize it, when the lime contained in the crop is deducted from the total lime required. This is given in the table on the next page.

[1] Breazeale, J. F., and LeClerc, J. A. The Growth of Wheat Seedlings as Affected by Acid or Alkaline Conditions. U. S. D. A., Bur. Chem., Bul. 149. 1912.

[2] Coville, F. V. The Agricultural Utilization of Acid Lands by Means of Acid-Tolerant Crops. U. S. D. A., Bul. No. 6, p. 5. 1913.

Weight, Lime Content, and Acidity of Green Manures to the Acre

Crop	Weight (tons)	Lime Content (pounds)	Acidity, as expressed in Lime Requirement (pounds)
Alfalfa	3½	130	267
Red clover	2	101	142
Cowpea	3½	92	300
Rye	2	11	178
Broom sedge	1	4	89

As decomposition proceeds the acids are oxidised, and finally basic material is held largely in combination with so-called humus of the soil. This is doubtless in the form of a colloidal complex, not a definite chemical compound. Analyses by Snyder[1] of purified humous ash from eight productive prairie soils have been averaged and are presented in tabular form in paragraph 97.

The quantity of basic material ordinarily held by the organic matter of the soil is small compared with the total soil content. The bases contained in humus are principally potassium and sodium — not calcium, as might be expected in the salt of an organic acid formed in the soil. Humus in the soil tends to overcome acidity and functions as an alkali. In respect to its composition and properties, much of it resembles a colloidal complex rather than a chemical combination of soil bases with organic acids.

It has often been observed that land from which forest has been cleared will yield good crops of red clover for

[1] Snyder, Harry. Soils. Minnesota Agr. Exp. Sta., Bul. 41. 1895.

several decades, after which it becomes more and more difficult to obtain a crop until the attempt must finally be abandoned. The change from forest to tillage has opened the way for an acid condition of soil, through the loss of bases carried off in the crops and the destruction of humus by tillage. The dissipation of humus is doubtless the more serious source of loss. Instances may be cited in which a farm has been so managed as to maintain the humus supply and the ability of the soil to produce red clover, although surrounding farms, on which humus has been depleted, have completely failed to grow this crop.

Apparently humus holds the basic constituents of the soil in a form in which they function as rather easily soluble salts, instead of locking them up as insoluble silicates. A given quantity of base in a soil is therefore more effective in preventing acidity by combining with weak acids, and possibly in forming carbonates, if the soil is well supplied with humus than if it is lacking in that constituent.

287. Effect of fertilizers on soil acidity. — That the continued use of ammonium sulfate on land may result in producing a sour condition has been shown by a number of investigators. The absorption and nitrification of the ammonia of that salt, and its final utilization by plants, leaves sulfuric acid, which combines with calcium and escapes in the drainage water. This may occur even when this fertilizer is used in quantities not excessive, but continued for many years, as has been shown by Gardner and Brown[1] at the Pennsylvania Experiment

[1] Gardner, F. D., and Brown, B. E. The Lime Requirement of the General Fertilizer Plots as Determined Periodically. Rept. Pennsylvania Agr. Exp. Sta., 1910–1911, pp. 25–60.

Station. Other fertilizers leaving an acid residue in the soil also act in this way. It is conceivable that potassium chloride and potassium sulfate might have a tendency to produce an acid condition, but the bases in these salts do not disappear from the soil so quickly as would ammonia, and consequently their action is slower.

The use of free sulfur on the land as a means of combating certain fungous diseases may lead to the formation of a sour soil through the oxidation of the sulfur with formation of sulfuric acid. Lint[1] has found that a soil in which sulfur was used at the rate of 600 pounds to the acre for prevention of potato scab, changed in its lime requirement from 2431 pounds to 4177 pounds as a result of the one treatment.

288. Acidity in relation to climate and to formation of soil. – In an arid or a semiarid climate soils are not likely to become sour. The great source of lime removal, leaching, operates to only a slight extent, or not at all, in a dry climate. The removal of bases in crops is apparently offset by the upward movement of bicarbonates in the capillary water. Experience shows that acidity is not a problem in soils of dry countries.

Soils that are derived from limestone or that have been mixed with limestone soils in the process of their formation are, under similar climatic conditions, less likely to become acid than are soils that originally contained less lime. The fact that a soil is derived from limestone, however, does not insure that it may not be benefited by an application of lime.

289. Weeds that flourish on sour soils. The acidity or the basicity of soils influences very greatly the growth

[1] Lint, H. Clay. The Influence of Sulfur on Soil Acidity. Jour. Indus. and Eng. Chem., Vol. 6, pp. 747-748. 1914.

of vegetation and determines to a large degree its nature. The flora undergoes a considerable variation as a soil changes from a basic to a sour condition. This is because some plants are injured to a greater extent than are others by the conditions that accompany an acid reaction of the soil. Some higher plants really grow better on a sour soil than they do on an alkaline one, but these form only a minority of the plants of agricultural importance. Weeds that abound and appear to flourish on acid soils may do so either because they grow better on sour soil than on basic, or because other vegetation growing on the soil does not thrive and therefore the dominant weeds of the region have less competition than they otherwise would have. There are certain weeds that may be taken to indicate a sour soil when present in large numbers. Some of these are found in one part of the country and some in another:—

WEEDS THAT FLOURISH ON SOUR SOILS

Common name	Botanical name
Sheep sorrel[1] . . .	*Rumex acetosella*
Paintbrush	*Hieracium aurantiacum*
Daisy	*Bellis perennis*
Horsetail rush[1] . .	*Equisetum arvense*
Corn spurry[2] . . .	*Spergula arvensis*
Wood horsetail[1] . .	*Equisetum sylvaticum*
Plantain[3] . . .	*Plantago major*
Goose grass[1] . . .	*Polygonum aviculare*

[1] Knisely, A. L. Acid Soils. Oregon Agr. Exp. Sta., Bul. 90, p. 23. 1906.

[2] Whitson, A. R., and Weir, W. W. Soil Acidity and Liming. Wisconsin Agr. Exp. Sta., Bul. 230, pp. 7-11. 1913.

[3] Voelcker, J. A. The Woburn Field Experiments. Jour. Royal Agr. Soc. England, Vol. 69, pp. 337-387. 1908.

290. Crops adapted to sour soils. There are some useful agricultural plants that grow better on sour soils than on alkaline soils, while other plants are apparently indifferent to the condition of the soil in this respect. As acid soils are of very common occurrence, and as the correction of this difficulty may not always be financially profitable or otherwise desirable, it is important to know what plants will thrive and how agricultural practice may be maintained on such soils. A list of these plants, based on different authorities, is herewith given: —

CROPS ADAPTED TO SOUR SOILS

Blueberry [1]	Hairy vetch [1]
Cranberry [2]	Crimson clover [1]
Strawberry [1]	Potato [1]
Blackberry [2]	Sweet potato [2]
Raspberry [2]	Rye [2]
Blackcap [2]	Millet [2]
Watermelon [2]	Buckwheat [1]
Turnip [2]	Carrot [1]
Red top [2]	Lupine [2]
Rhode Island bent-grass [2]	Serradella [1]
Cowpea [1]	Radish [2]
Soybean [1]	Velvet bean [2]
Castor bean [2]	

The very considerable number of these plants, and especially the inclusion among them of legumes that may be grown for soil improvement, suggest the posi

[1] Coville, F. V. The Agricultural Utilization of Acid Lands by Means of Acid-Tolerant Crops. U. S. D. A., Bul. No. 6, pp. 7-12. 1913.

[2] Wheeler, H. J. The Liming of Soils. U. S. D. A., Farmers' Bul. 77. 1905.

bility of a successful agricultural practice on acid soils where the important money crop to be grown, or some other condition, would make it undesirable to correct the soil acidity. There are certain crops, such as blueberries and cranberries, that require an acid soil; there are others, such as potatoes, that may suffer less from disease if the soil is sour. These crops are sometimes the ones that are of greatest financial importance in a region, and it therefore becomes desirable to maintain an acid condition of soil.

281. Crops that are injured by acid soils. There are many plants that are injured by a sour condition of the soil, and these include some of the most important farm crops. It should therefore be borne in mind that for most farm practice an acid soil is very undesirable. One notable reason for this is that such crops as red clover and alfalfa, which are of great value both as a means of improving soil and for hay, can be grown only with great uncertainty or not at all on acid soils.

CROPS THAT ARE INJURED BY SOUR SOILS[1]

Alfalfa	Salsify	Cauliflower
Red clover	Squash	Cabbage
Saltbush	Spinach	Cucumber
Timothy	Red beet	Lettuce
Kentucky blue-grass	Sorghum	Onion
Maize	Barley	Okra
Oats	Sugar beet	Peanut
Pepper	Currant	Tobacco
Parsnip	Mangel-wurzel	Kohlrabi
Pumpkin	Celery	Eggplant

[1] Wheeler, H. J. The Liming of Soils. U. S. D. A., Farmers' Bul. 77 (revised). 1905.

While soils may be either sour or alkaline, there are also degrees of sourness. Thus a soil may be so sour as to completely prevent the growth of one kind of plant and yet produce excellent crops of another plant which would have perished if the soil had been more acid. For example, red clover will grow fairly well on soil that is too sour to raise alfalfa.

292. Qualitative tests for acidity. — A simple test to indicate an acid condition of soil is not so easy of execution nor so infallible in its prediction as might be desired. The object of such a test is to ascertain whether a soil is not well adapted to the growth of certain plants and whether the application of lime would benefit it in this respect. A number of tests have been proposed which will be outlined and briefly discussed.

293. Litmus paper test. — Blue litmus paper is brought into contact with the wet soil. A rapid and decided change to red is taken to indicate an acid condition of the soil. Carbonic acid, which is always present in soils, is supposed to give only a faint pink color to the litmus paper. Various ways of bringing the paper into contact with the soil have been recommended, among others the interposing of filter paper between the soil and the litmus paper.[1] It is also generally pointed out that the acid perspiration on the fingers may lead to delusion.

A criticism of the test has been made by Cameron,[2] who states that the absorbent action of soils for bases is greater than is that of paper, while for acids the reverse

[1] Kellerman, K. F., and Robinson, T. R. Legume Inoculation and the Litmus Reaction of Soils. U. S. D. A., Bur. Plant Indus., Circ. 71, pp. 3–11. 1910.

[2] Cameron, F. K. The Soil Solution, pp. 65–68. Easton, Pennsylvania. 1911.

is the case. Consequently the base that had produced the blue color is absorbed from the litmus, leaving the acid compound, which is red. Cameron concludes that the test is unreliable, and proposes to extract the soil with water, boil it in order to expel carbon dioxide, and then test the reaction of the solution.

Much litmus paper that is sold is of very poor quality; but when good paper is used and the test is carefully made, the general experience has been that it is a fairly good, although not an infallible, guide to the need of a soil for lime. Red coloration due to absorptive action is probably an advantage rather than a source of error in the test, as a soil strongly absorptive of bases is likely to need lime. This coloration does not necessarily indicate the presence of free acid, but merely need of lime.

204. Ammonia test. — In this test the soil is stirred with a dilute solution of ammonia hydroxide. After settling, if the supernatant liquid on standing takes on a dark chocolate or a black color it is said to be acid. This method, which has been proposed by Müntz,[1] is not of general application and would not always be reliable in the case of soils of arid regions. The depth of color is not a guide to the degree of acidity, since many acid soils are low in organic matter.

205. Zinc sulfide test. — A test recently proposed by Truog[2] consists in mixing the soil to be tested with a small quantity of calcium chloride and a very little zinc sulfide. Water is added and the mixture is heated to

[1] Wheeler, H. J., Hartwell, B. L., and Sargent, C. L. Chemical Methods for Ascertaining the Lime Requirements of Soils. Rhode Island Agr. Exp. Sta., Bul. 62, pp. 53-68. 1899.

[2] Truog, E. A. New Method for the Determination of Soil Acidity. Science, N. S., Vol. 40, pp. 246-248. 1914.

boiling. A strip of moistened lead acetate paper is held over the mouth of the flask for two minutes while the boiling proceeds. If the soil is acid, the paper will be darkened on the underside; if the soil is not acid, no darkening will occur.

This method is evidently designed to test the need of the soil for lime as well as actual acidity, for the absorption of calcium from the dissociated chloride would leave free hydrochloric acid. The action of this acid on zinc sulfide would generate hydrogen sulfide, thus blackening the lead acetate paper.

A somewhat similar principle is involved in the proposal to use a solution of potassium nitrate in the litmus paper test.

296. Litmus paper and potassium nitrate. — This is performed in the same manner as the former litmus paper test, except for the substitution of a saturated solution of potassium nitrate instead of distilled water for moistening the soil.

297. Acid test for carbonates. — In this test a dry sample of the soil is treated with a few drops of dilute hydrochloric acid. Effervescence indicates the presence of carbonates or bicarbonates in sufficient quantities to insure an alkaline soil, although sometimes lime may still be beneficial.

Whitson and Weir [1] have objected to this method on the ground that the displacement of air in the pore spaces of the soil by the dilute acid may be mistaken for evolution of carbon dioxide. In the hands of an experienced and careful operator this would not necessarily invalidate the method.

[1] Whitson, A. R., and Weir, W. W. Soil Acidity and Liming. Wisconsin Agr. Exp. Sta., Bul. 230, pp. 7-11. 1913.

298. Plants as indicators of acidity. — In addition to these chemical tests for acidity there may also be mentioned what is perhaps the most reliable indication of the need of lime, namely, the failure of a soil to produce red clover, and the presence of those weeds that have previously been shown to thrive on sour soil (par. 289). When a soil bears this relation to the plant growth it may safely be assumed that those plants included in the list of crops that are injured by sour soils will yield better if the soil is limed than if it is not so treated. The crops adapted to sour soils may not be injured.

299. Quantitative determinations of acidity. — A number of quantitative methods for determining the degree of acidity or the lime requirements of soils have been devised. Only a few of these need be mentioned.

300. Potassium nitrate method.[1] — The soil is shaken with a normal solution of potassium nitrate for three hours, and then allowed to stand overnight. An aliquot portion of the supernatant liquid is boiled in order to expel carbon dioxide, and when cool it is titrated with a standard solution of sodium hydroxide.

This method does not estimate either the free acid or the lime requirement of the soil. What it does is to give the absorptive power of the soil for potassium when in equilibrium with a solution containing the acid with which the potassium was originally in combination. There is a substitution of bases during the contact of the nitrate solution with the soil, and a partial decomposition of these salts during the titration with alkali.

[1] Official and Provisional Methods of Analysis. Association of Official Agricultural Chemists. U. S. D. A., Bur. Chem., Bul. 107 (revised), p. 20. 1908.

301. **Limewater method.** — A measured quantity of a standard solution of limewater is brought into contact with the soil and absorption is accomplished by evaporation, after which water is added and the filtrate is tested with phenolphthalein. Failure to produce a pink color shows that the lime requirement of the soil has not been reached; an alkaline reaction shows that an excess of lime has been added. A number of tests must be made in order to reach a point below which the indicator shows no color and above which it does. The lime requirement may thus be indicated. This determination was devised by Veitch,[3] and is a useful method since it indicates to within a few hundred pounds the quantity of lime required to satisfy the absorptive power of a soil.

302. **Résumé.** — In conclusion, a few facts regarding so-called acid soils may be restated: (1) acidity is not always due to free acids, but often to the lack of an abundance of bases; (2) it is not injurious to all plants, but is likely to depress the yields of the majority of agriculturally important crops, while some valuable ones are benefited by it; (3) it may be overcome sometimes by aeration of the soil, and always by the application of lime or wood ashes. The correction of acidity by means of lime will be discussed in a later chapter, as will also the relation of certain bacteria to acidity.

[3] Veitch, F. P. The Estimation of Soil Acidity and the Lime Requirements of Soils. Jour. Am. Chem. Soc., Vol. 24, pp. 1120-1128. 1902.

CHAPTER XVIII

ALKALI SOILS

It has already been shown that soils are acted upon by a great variety of weathering agents which gradually render soluble a portion of the most susceptible constituents. This soluble material becomes a part of the soil solution and may come in contact with the roots of any crop growing on the soil. In humid regions, where a large quantity of water percolates through the soil, this soluble matter has little opportunity to collect. In arid regions, however, where loss by drainage is slight, these salts may often collect in large amounts. During periods of drought they are carried upward by the capillary rise of the soil water, while during periods of rainfall they may move downward again in proportion to the leaching action. At one time the lower soil may contain considerably more soluble salt than the upper; at another time the condition may be reversed, in which case the solution in contact with plant roots may contain so much soluble matter that vegetation is injured or destroyed. This excess of soluble salts usually has a marked alkaline reaction, but in any case it produces what is termed an alkali soil.

303. **Composition of alkali salts.** — The materials dissolved in the soil water consist of all the substances found in the soil, but as the rates of solubility of these substances vary greatly there is accumulated a much larger quantity of some substances than of others. Carbonates, sulfates,

and chlorides of sodium, potassium, calcium, and magnesium occur in the largest amounts. Sodium may be present as carbonate, sulfate, chloride, phosphate, and nitrate. Potassium may be similarly combined. Magnesium is likely to appear as a sulfate or a chloride, and calcium as a sulfate, a chloride, or a carbonate. One salt will predominate in some soils, and other salts in other soils. A base may be present in combination with several different acids. The nature of the prevailing salt greatly influences the effect on vegetation. The table on page 393 gives the composition of the soluble salts from a number of alkali soils.

A few years ago Headden[1] called attention to large accumulations of nitrates in certain localities in Colorado. These salts dissolve in the soil water and are frequently present in such large quantities as to be injurious to vegetation.

304. White and black alkali. — Sulfates and chlorides of the alkalies, when concentrated on the surface of the soil, produce a white incrustation, which is very common in alkali regions during a dry period as a result of evaporation of moisture. Incrustations of this character are called white alkali.

Carbonates of the alkalies, particularly sodium carbonate, dissolve organic matter from the soil, thus giving a dark color to the solution and to the incrustation. For this reason alkali containing large quantities of these salts is called black alkali. Black or brown alkali may also be produced by calcium chloride or by an excess of sodium nitrate.

[1] Headden, W. P. Deterioration in the Quality of Sugar Beets due to Nitrates Formed in the Soil. Colorado Agr. Exp. Sta., Bul. 183. 1912.

PERCENTAGE COMPOSITION OF ALKALI SALTS IN SOILS

	Colorado Exp. Sta.[1]	California (Tulare) Exp. Sta.[2]	Yakima, Washington, 12–24 Inches[3]	Billings, Montana[4]		Yuma, Arizona[5]	
				Crust	Surface 24 In.	Crust	0–12 Inches
KCl	1.64	–	5.81	—	..	4.00	22.10
K_2SO_4	—	3.95	—	1.60	21.41	—	—
K_2CO_3	—	—	9.73	—	—	—	—
Na_2SO_4	—	25.78	—	85.57	36.12	..	—
$NaNO_3$	39.07	19.78	—	—	—	—	—
Na_2CO_3	—	32.58	13.86	—	7.28	—	—
$NaCl$	1.61	14.75	—	0.55	—	81.15	13.77
Na_2HPO_4	—	2.25	—	—	—	—	—
$MgSO_4$	—	—	—	8.90	4.06	—	0.88
$MgCl_2$	12.71	—	—	—	—	7.71	3.08
$CaCl_2$	17.29	—	—	—	—	0.25	—
$NaHCO_3$	—	–	26.72	0.67	22.06	0.28	21.02
$CaSO_4$	21.48	—	1.87	2.71	10.07	6.61	32.25
$Ca(HCO_3)_2$	—	—	16.48	—			
$Mg(HCO_3)_2$	–	—	16.73	—			—
$(NH_4)_2CO_3$	—	1.41	—	—	—		—

[1] Headden, W. P. The Fixation of Nitrogen. Colorado Agr. Exp. Sta., Bul. 155, p. 30. 1910.

[2] Hilgard, E. W. Soils, p. 442. New York, 1906.

[3] Dorsey, C. W. Alkali Soils of the United States. U. S. D. A., Bur. Soils, Bul. 35, p. 79. 1906.

[4] Ibid., p. 108. [5] Ibid., p. 109.

Black alkali is much more destructive to vegetation than is white. A quantity of white alkali that would not seriously interfere with the growth of most crops might completely prevent the development of useful plants if the alkali were black.

305. Effect of alkali on crops. — The presence of relatively large amounts of salts dissolved in water and brought into contact with a plant cell has been shown to cause a shrinkage of the protoplasmic lining of the cell, the shrinking increasing with the concentration of the solution. This causes the plant to wilt, to cease growth, and finally to die. The nature of the salt, and the species and even the individuality of the plant, determine the point of concentration at which the plant succumbs.

The directly injurious effect of the chlorides, sulfates, nitrates, and other salts of the alkalies and alkali earths is due to this action on the cell contents of the plants. The carbonates of the alkalies have, in addition, a corroding effect on the plant tissues, dissolving the parts of the plant with which they come in contact. Indirectly alkali salts may injure plants by their influence on the soil tilth, soil organisms, and fungous and bacterial diseases.

306. Effect on different plants. — The factors that determine the tolerance of plants toward alkali are: (1) the physiological constitution of the plant; (2) the rooting habit. The first is not well understood, but resistance varies with species, and even with individuals of the same species. So far as the rooting habit influences tolerance of alkali, the advantage is with the deep-rooted plants such as alfalfa and sugar beets, probably because a part of the root is in a less strongly impregnated part of the soil.

Of the cereals, barley and oats are the most tolerant, these being able in some cases to produce good crops on soil containing two-tenths per cent of white alkali. Of the forage crops, a number of valuable grasses are able to grow on soil containing considerably more than two-tenths per cent of alkali. Timothy, smooth brome, and alfalfa are the cultivated forage plants most tolerant of alkali, although they do not equal the native grasses in this respect. Cotton also tolerates a considerable amount of alkali.

Loughridge,[1] after experiments and observation for a number of years, has obtained data regarding the resistance of various crops to the several alkali salts. His results are given in part below, expressed in pounds to an acre to a depth of four feet: —

Crop	Na_2SO_4	Na_2CO_3	NaCl	Total Alkali
Grapes . . .	40,800	7,550	9,640	45,760
Oranges . . .	18,600	3,840	3,360	21,840
Pears . . .	17,800	1,760	1,360	20,960
Apples . . .	14,240	640	1,240	16,120
Peaches . . .	9,600	680	1,000	11,280
Rye	9,800	960	1,720	12,480
Barley . . .	12,020	12,170	5,100	25,520
Sugar beets .	52,640	4,000	5,440	59,840
Sorghum . .	61,840	9,840	9,680	81,360
Alfalfa . . .	102,480	2,360	5,760	110,320
Saltbush . .	125,640	18,560	12,520	156,720

[1] Loughridge, R. H. Tolerance of Alkali by Various Cultures. California Agr. Exp. Sta., Bul. 133. 1901. See also Kearney, T. H., and Harter, L. L. Comparative Tolerance of Various Plants for the Salts Common in Alkali Soils. U.S.D.A., Bur. Plant Indus., Bul. 113. 1907.

Although in general the results as to the resistance to alkali of the various crops are so conflicting, the Bureau of Soils,[1] in its alkali mapping, has been able to make a rough classification as follows: —

Percentage of Total Salts	Percentage of Black Alkali	Crops
0 to 0.20	Less than 0.05	All crops grow
0.20 to 0.40	0.05 to 0.10	All but most sensitive
0.40 to 0.60	0.10 to 0.20	Old alfalfa, sugar beet, barley, and sorghum
0.60 to 1.00	0.20 to 0.30	Only most resistant plants
1.00 to 3.00	0.30 and above	No plants

307. Other conditions that influence the action of alkali. — The higher the water content of the soil, the less is the injury to plants from alkali; but should the same soil become dry, the previous large quantity of water would, by bringing into solution a larger amount of alkali, render the solution stronger than it would otherwise have been, and thus cause greater injury (see Fig. 57).

The distribution of the alkali at different depths may have an important bearing on its effect on plants. Young plants and shallow-rooted crops may be entirely destroyed by the concentration of alkali at the surface, while the same quantity evenly distributed through the soil, or carried by moisture to a lower depth, would have caused no injury. A loam soil, by reason of its greater water-holding capacity and adsorptive power, will carry more alkali without injury to plants than will a sandy

[1] Dorsey, C. W. Alkali Soils of the United States. U. S. D. A., Bur. Soils, Bul. 35, pp. 23-25. 1906.

soil. Certain of the alkali salts exert a deflocculating action on clay soils and effect an indirect injury in that way.

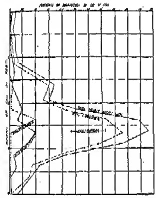

FIG. 87.—Diagram showing the amount and composition of alkali salts at various depths. Tulare, California.

308. Accumulation of alkali.—The alkali salts, being readily soluble, are carried by the soil water where there is any lateral movement, as is often the case where land slopes to some one point. Low-lying lands adjacent to such slopes are thus likely to contain considerable alkali, and the "alkali spots" of semiarid regions and the large accumulations of alkali in many of the valley lands of arid regions are traceable to this cause.

309. Irrigation and alkali. In irrigated regions, the injurious effect of alkali is in many cases discovered only

after irrigation has been practiced for a few years. This is due to what is known as a "rise of alkali," and comes about through the accumulation, near the surface of the soil, of salts that were formerly distributed throughout a depth of perhaps many feet. Before the land was irrigated, the rainfall penetrated only a slight depth into the soil, and when evaporation took place, salts were drawn to the surface from only a small volume of soil. When, however, irrigation water is turned on the land, the soil becomes wet to a depth of perhaps fifteen or twenty feet. During the portion of the year in which the soil is allowed to dry, large quantities of salts are carried toward the surface by the upward-moving capillary water. Although these salts are in part carried down again by the next irrigation, the upward movement constantly exceeds the downward one. This is because the descending water passes largely through the non-capillary interstitial spaces, while the ascending water passes entirely through the capillary spaces. The smaller spaces, therefore, contain a considerable quantity of soluble salts after the downward movement ceases and the upward movement begins. In other words, the volume of water carrying the salts downward in the capillary spaces is less than that carrying them upward through these spaces. Surface tension causes the salts to accumulate largely in the capillary spaces, and it is therefore the direction of the principal movement through these spaces that determines the point of accumulation of the alkali.

There are large areas of land in Egypt, in India, and even in France and Italy, as well as in this country, that have suffered in this way, and not infrequently they have reverted to a desert state.

310. **The handling of alkali lands.**[1] — Ordinarily there are two general ways in which alkali lands may be handled in order to avoid the injurious effect of soluble salts. The first of these is eradication, the second may be designated as control. In the former case, an attempt is made to actually eliminate by various means some of the alkali. In the latter, methods of soil management are employed which will keep the salts well distributed throughout the soil. In many cases soils would grow excellent crops if the alkali could only be kept well distributed through the soil layers so that no toxic action could occur, at least within the root zone. In general, steps should always be taken toward the control of alkali, whether eradication is attempted or not. Under irrigation, careful control is always wise.

311. **Eradication of alkali.** — Of methods designed to at least partially free the soil of alkali, the commonest are: (1) leaching with underdrainage, (2) correction with gypsum, (3) scraping, and (4) flushing.

312. **Leaching with underdrainage.** — Of the various methods for removing an excess of soluble salts, the use of tile drains is the most thorough and satisfactory. When this method is used in an irrigated region, heavy and repeated applications of water must be made, to leach out the alkali from the soil and drain it off through the tile. When used for the amelioration of alkali spots

[1] Dorsey, C. W. Reclamation of Alkali Soils. U. S. D. A., Bur. Soils, Bul. 34. 1906. Also, Hilgard, E. W. Utilization and Reclamation of Alkali Lands, Soils. New York, 1911. Also, Brown, C. F., and Hart, R. A. Reclamation of Seeped and Alkali Lands. Utah Agr. Exp. Sta., Bul. 111. 1910. Also, Dorsey, C. W. Reclamation of Alkali Soils at Billings, Montana. U. S. D. A., Bur. Soils, Bul. 44. 1907.

in a semiarid region, the natural rainfall will in time effect the removal.

In laying tiles it is necessary to have them at such a depth that soluble salt in the soil beneath them will not readily rise to the surface. This will depend on those properties of the soil governing the capillary movement of water. Three or four feet in depth is usually sufficient, but the capillary movement should first be estimated.

After the drains have been placed, the land is flooded with water to a depth of several inches. The water is allowed to soak into the soil and to pass off through the drains, leaching out part of the alkali in the process. Before the soil has time to become very dry the flooding is repeated, and the operation is kept up until the land is brought into a satisfactory condition.

Crops that will stand flooding may be grown during this treatment, and they will serve to keep the soil from puddling, as it is likely to do if allowed to become dry on the surface. If crops are not grown, the soil should be harrowed between floodings. The operation should not be carried to a point where the soluble salts are reduced below the needs of the crop, or so low that they lose entirely their effect on the retention of moisture.

313. Correction with gypsum. — The use of gypsum on black alkali land has sometimes been practiced for the purpose of converting the alkali carbonates into sulfates, thus ameliorating the injurious properties of the alkali without decreasing the amount. The quantity of gypsum required may be calculated from the amount and composition of the alkali. The soil must be kept moist, in order to bring about the reaction, and the

gypsum should be harrowed into the surface, not plowed under. The reaction is as follows: —

$$Na_2CO_3 + CaSO_4 = CaCO_3 + Na_2SO_4$$

When soil containing black alkali is to be tile-drained, it is recommended that the land shall first be treated with gypsum, as the substitution of alkali sulfates for carbonates causes the soil to assume a much less compact condition and thus facilitates drainage. It also prevents the loss of organic matter dissolved by the carbonate of soda and the soluble phosphates, both of which are precipitated by the change.

214. Scraping. Removal of the alkali incrustation that has accumulated at the surface is sometimes resorted to. Very often the rise of alkali is encouraged by applications of irrigation water, which is allowed to evaporate unretarded. The salts are thus carried upward by the capillary movement of the soil water. This method of alkali eradication is never very efficient, and is often dangerous, as it encourages the presence of very large amounts of alkali salts in the surface soil.

215. Flushing. — Often alkali accumulations may be washed from the soil surface by turning on a rapidly moving stream of water. The texture of the soil, as well as the slope of the land, must be just right for such a procedure. Generally so much water enters the soil that the land remains heavily impregnated with alkali salts. Both this method and the previous one, even if successful, are only temporary. Moreover, lands carrying so much alkali as to admit of either one of these procedures may be so heavily charged as never to yield to any form of either eradication or control.

316. Control of alkali. — Where excessive amounts of soluble salts do not exist in a soil, the control of the alkali with a view of keeping it well distributed in the soil column is the best practice. The retardation of evaporation is, of course, the main object in this procedure. The intensive use of the soil mulch is therefore to be advocated, especially in all irrigation operations where alkali concentrations are likely to occur. Such a method of soil management not only saves moisture, but also prevents the excessive translocation of soluble salts into the root zone. This method of control is the most economical, the cheapest, and the one to be advocated on all occasions, no matter what may have been the previous means of dealing with the alkali situation.

317. Cropping with tolerant plants. — Certain soils that are strongly impregnated with alkali may be gradually improved by cropping with sugar beets and other crops that are tolerant of alkali and that remove large quantities of salts. This is more likely to be efficacious where irrigation is not practiced. Certain crops, moreover, while somewhat seriously injured while young, are very resistant once their root systems are developed. A good example is alfalfa, the young plants being very tender while the more mature ones are extremely resistant. Temporary eradication of alkali may allow such a crop to be established. It will then maintain itself in spite of the concentrations that may later occur.

318. Alkali spots. — In semiarid regions small areas of alkali are often found, varying from a few square yards to several acres in size. The quantities of alkali in these are usually not sufficient to prevent the growth of plants in years of good rainfall, but in periods of drought the concentration of the salts and the compact condition that

they tend to produce combine to injure the crop. The methods already mentioned for treating alkali land are of service on these small areas, and, in addition, the plowing-under of fresh farm manure has been found to improve their productiveness. This, with surface drainage, deep tillage, and good cultivation in order to prevent the soil from drying out, will usually remedy the difficulty. In many cases these spots become highly productive under proper treatment.

CHAPTER XIX

ABSORPTION OF NUTRITIVE SALTS BY AGRICULTURAL PLANTS

ALL the salts taken up by the roots of agricultural plants are in solution when absorbed. The movement into the root thus depends on the presence of moisture, which is the medium of transfer. The root-hairs are the great absorbing organs of the plant, and through the cells of their delicate tissues the solutions of the various salts are passed.

319. How plants absorb nutrients. — The nature and quantity of material absorbed by a plant is determined by the law of diffusion. From the cells of the root-hairs the dissolved salts are transferred to other parts of the plant, where they undergo the metabolic processes that determine which constituents shall be retained in the tissues of the plant. The unused ions that remain in the plant juices prevent by their presence the further absorption of those particular substances from the soil water. It thus happens that the composition of the ash of a plant may be very different from that of the substances presented to it in solution. For example, aluminium, although always present in the soil in a very slightly soluble form, is present in mere traces in the ash of most plants. On the other hand, iodine, although present in sea water only in the most minute quantities, is present in large quantities in the ash of certain marine algae.

A plant will, in general, take up more of a nutritive substance if it is presented in large amount, as compared with the other soluble substances in the nutrient solution, than if it is presented in small amount. Thus, the percentage of nitrogen in maize, oats, and wheat may be increased by increasing the ratio of nitrogen to other nutritive substances in the nutrient media. This is also true of potassium and phosphorus, respectively. This fact is accounted for by the maintenance of the diffusive equilibrium at a higher level for a particular ion which is relatively abundant in the nutrient solution, thus preventing the return of the excess from the plant.

320. Relation between root-hairs and soil particles. — In a rich, moist soil the number of root-hairs is very great, while in a poor or a very dry soil or in a saturated soil there are comparatively few root-hairs. The connection between the root-hairs and the soil particles is extremely intimate. When in contact with a particle of soil, a root-hair in many cases almost incloses it, and by means of its mucilaginous wall forms a contact so close as practically to make the solution between the particle and the cell wall distinct from that between the soil particles themselves.[1]

There has been considerable difference of opinion as to how a plant can obtain its mineral nutrients from a substance so difficultly soluble as the soil. This has arisen because of the conflicting nature and the inadequate character of the data available.

321. Liebig and Sachs on solvent action of plant roots. — Liebig[1] called attention to the fact that a plant may obtain one hundred times as much phosphorus and

[1] Liebig, J. Die Chemie in ihrer Anwendung auf Agrikultur. 1862.

nitrogen and fifty times as much potassium as can be extracted from the same volume of soil with pure water or with water containing carbon dioxide. It has, of course, been recognized that the soil water is aided in its solvent action by a variety of substances that may be normally present in solution, beginning with the gases taken up by rain in its descent through the atmosphere, and further added to by the carbon dioxide and the organic and mineral substances obtained from the soil. It has been held that the plant roots aid solution of mineral matter by excretion of acids, which act effectively as solvents. The well-known root tracings on limestone and marble have been taken as proof of the excretion of such acids. Sachs,[1] and later other investigators, grew plants of various kinds in soil and other media in which was placed a slab of polished marble or dolomite or calcium phosphate, covered with a layer of washed sand. After the plants had made sufficient growth the slabs were removed, and on the surfaces were found corroded tracings, corresponding to the lines of contact between the rootlets and the minerals.

322. Czapek's experiments. — In order to test this theory, Czapek[2] repeated the experiments of Sachs, using plates of gypsum mixed with the ground mineral that he wished to test, and this mixture he spread over a glass plate. Using these plates in the same manner as previously described, Czapek found that, while plates of calcium carbonate and of calcium phosphate were corroded by the plant roots, plates of aluminium phosphate

[1] Sachs, J. Auflösung des Marmors durch Mais-Wurzeln. Bot. Zeitung, 18 Jahrgang, Seite 117–119. 1860.

[2] Czapek, F. Zur Lehre von den Wurzelausscheidung. Jahrb. f. Wiss. Bot., Band 29, Seite 321–390. 1896.

were not. He concludes that if the tracings are due to acids excreted by the plant roots, the acids so excreted must be those that have no solvent action on aluminium phosphate. This would limit the excreted acids to carbonic, acetic, propionic, and butyric. Czapek also replies to the argument that the acids producing the tracings must be non-volatile ones because of the definite lines made in the mineral, by stating that the excretion of carbon dioxide alone would be sufficient to account for the observations since it dissolves in water to form carbonic acid, and that carbonic acid is always present in the cell walls of the root epidermis. By means of microchemical analyses of the exudations of root-hairs grown in a water-saturated atmosphere, Czapek found potassium, magnesium, calcium, phosphorus, and chlorine in the exudate. He concludes that the solvent action of plant roots is due to acid salts of mineral acids, particularly acid potassium phosphate. He has not proved, however, that the exudations were not from dead root-hairs nor from the dead cells of the rootcap. In either case they would have some solvent action, but whether sufficient to make them of importance is doubtful.

323. **Secretion of an oxidizing enzyme by plant roots.** — Molisch[1] found that root-hairs secrete a substance having properties corresponding to those of an oxidizing enzyme. His work has been repeated by others who have failed to obtain similar results, but lately Schreiner and Reed[2] have

[1] Molisch, H. Ueber Wurzelausscheidungen und deren Einwirkung auf Organische Substanzen. Sitzungsber. Akad. Wiss. Wien-Math. Nat., Band 96, Seite 84–108. 1888. Abstract in Chem. Centrlb., Band 18, Seite 1511, 1888, and in Centrlb. f. Agr. Chem., Band 17, Seite 128, 1888.

[2] Schreiner, Oswald, and Reed, H. S. Studies on the Oxidizing Powers of Roots. Bot. Gazette, Vol. 47, p. 355. 1909.

demonstrated an oxidizing action of roots that is apparently due to a peroxidase. Oxidation alone, however, would hardly suffice to account for the solvent action accompanying the development of plant roots, although it is doubtless an important function and useful in other ways.

224. Importance of carbon dioxide as a solvent.— Stoklasa and Ernst[1] have contributed much to this subject during the last decade. Stoklasa's earlier experiments, conducted by maintaining the plant roots in a saturated atmosphere, gave only carbon dioxide in the exudate. In this he is in agreement with most of the recent investigators of this subject. Stoklasa emphasizes the importance of carbon dioxide as a solvent by showing the quantity produced by plants and by microörganisms. He estimates that in one acre of soil to a depth of sixteen inches there are sixty-eight pounds of carbon dioxide produced by bacterial respiration in two hundred days, and fifty-four pounds of carbon dioxide excreted by plant roots in one hundred days; these periods he considers as representing the year's activity of bacteria and higher plants.

In later experiments, Stoklasa and Ernst[2] found that when plants do not have a sufficient supply of oxygen in the air surrounding their roots, they secrete acetic and formic acids from the root-hairs. These investigators believe that these acids are toxic rather than beneficial,

[1] Stoklasa, J., and Ernst, A. Ueber den Ursprung die Menge und die Bedeutung des Kohlendioxyds im Boden. Centrlb. f. Bakt. II, Band 14, Seite 723–736. 1905.

[2] Stoklasa, J., and Ernst, A. Beiträge zur Lösung der Frage der Chemischen Natur des Wurzelsekretes. Jahrb. f. Wiss. Bot., Band 46, Seite 55–102. 1908–1909.

and that they are responsible, in large measure, for the injurious effect on plants of a very compact condition of soil. In the same communication these authors report an experiment in which it was found that the kinds of plants that excrete the largest quantity of carbon dioxide from their roots are the ones that absorb the greatest quantities of phosphorus from gneiss and from basalt. This, however, does not necessarily connote any consequential relation between these physiological functions.

Barakov[1] drew air through planted soils contained in large tanks. He found that the maximum production of carbon dioxide occurred at the time when the plants were blossoming, whether the plants blossomed early or late in the season. This he considered to indicate that the plant assists most vigorously in the solution of nutrient materials at the time when it is most active in absorbing them.

325. Insufficiency of carbon dioxide. — Pfeiffer and Blanck[2] passed carbon dioxide through soil contained in vessels in which plants were growing. The soil in some vessels contained a difficultly soluble tricalcic phosphate, that in other vessels the more easily soluble dicalcic phosphate, and that in still other vessels was unfertilized. Another set of vessels having the same fertilizer treatment received no carbon dioxide. The soil receiving carbon dioxide produced larger yields of dry matter and phosphorus in

[1] Barakov, P. The Carbon Dioxide Content of Soils at Different Periods of Plant Growth. Jour. Exp. Agr. (Russian), Vol. 11, pp. 321–342. 1910. The authors are indebted to Dr. J. Davidson for a translation of this paper.

[2] Pfeiffer, Th., and Blanck, E. Die Säureausscheidung der Wurzeln und die Löslichkeit der Bodennährstoffe in Kohlensäurehaltigem Wasser. Landw. Vers. Stat., Band 77, Seite 217–268. 1912.

the crop on the soil to which dicalcic phosphate had been applied than did the soil not receiving carbon dioxide; but the soil to which no phosphate was added yielded equally well whether it received carbon dioxide or not. The plants used were oats, peas, and lupines. These investigators conclude that carbon dioxide is not a sufficient solvent to account for the mineral nutrients obtained from soils by plants.

226. The present status of the question. The available evidence on excretion of acids other than carbonic by the roots of plants does not admit of any very satisfactory conclusion as to their relative importance in the acquisition of plant-food materials. There can be no doubt, however, that carbon dioxide resulting from root exudation and from decomposition of organic matter in the soil plays a very prominent part in this operation. The very large quantity of carbon dioxide in the soil, amounting in some cases to from .5 to nearly 10 per cent of the soil air, or several hundred times that of the atmospheric air, must aid greatly in dissolving the soil particles.

Whatever may be the concentration of the soil water, it seems probable that the liquid which is found where the root-hair comes in contact with the soil particle, and which is separated, in part at least, from the remainder of the soil water, must have a density much greater than that found elsewhere in the soil. That portion of the soil water immediately in contact with the soil grain is a much stronger solution than the water farther from the soil surfaces, because of the adsorptive action of the particles.

Many plants grown in solutions of nutritive salts have few or no root-hairs, but absorb through the epidermal

tissue of the roots. If the plant depended wholly on the prepared solution in the soil water, a similar structure would doubtless suffice. The special modification by which the root-hairs come in intimate contact with the soil particle and almost surround it, indicates a direct relation between the soil particles and the plant, and not merely between the soil solution and the plant.

New root-hairs are constantly being formed, and the old ones become inactive and disappear. The contact of a root-hair with a soil particle is not long-continued. Whether the period of contact is determined by the ability of the root to absorb nutriment from the particle is not known. Certain it is that only a small portion of the particle is removed.

387. Possible root action on colloidal complexes.— It has already been stated that there is some evidence to lead to the belief that the surfaces of soil particles are covered to a large extent with colloidal complexes, composed of both organic and inorganic matter having vigorous absorptive properties and holding the bases and phosphorus in an absorbed condition. Roots of growing plants have been found to cause coagulation of at least some colloids, possibly by leaving an acid residue in the nutrient solution by reason of the selective absorption of bases and rejection of the acids of the dissolved salts. It is conceivable that the root-hair, by removing bases from the solution existing between the cell wall and the colloidal covering of the soil particle, may cause coagulation of the colloidal matter and thus liberate the plant-food materials held by absorption. The liberated material, being of a readily soluble nature, would be taken up by the solution between the rootlet and the soil particle, from which the root-hair could readily absorb it. Such

an hypothesis would account for the ability of plants to obtain a quantity of nutrient materials far in excess of what can be accounted for by the solvent action of pure water, and even beyond what many investigators are willing to attribute to the solvent action of water charged with carbon dioxide.

328. Why crops vary in their absorptive powers. As has already been pointed out (pars. 331–336), crops of different kinds vary greatly in their ability to draw nourishment from the soil. The difference between the nitrogen, phosphorus, and potassium taken up by a corn crop of average size and a wheat crop of average size is very striking. In the table on page 419 it is seen that two tons of red clover contain three times as much potash, nearly ten times as much lime, and somewhat more phosphoric acid than does a crop of thirty bushels of wheat including the straw.

The difference in absorbing power may be due to either one or both of two causes: (1) a larger absorbing system; (2) a more active absorbing system. The former is determined by the extent of the root-hair surfaces; the latter by the intensity of the absorbing action.

329. Extent of absorbing system. — Plants with large root systems may be expected to absorb the larger amounts of nutrients from the soil. Such is usually the case, although the extent of the root system is not necessarily proportional to the total area of the absorbing surfaces of the root-hairs.

330. Absorptive Activity. — The absorptive activity of a plant under any given condition of soil and climate depends on: (1) the rapidity and completeness with which the plant elaborates the substances taken from the soil into plant substance, or otherwise removes them from

solution; (2) the extent to which the exudations from the root-hairs — whether these be carbon dioxide, salts of mineral acids, or organic acids — act on the soil particles.

The first of these is a function of the vital energy of the plant and its ability to utilize sunshine and carbon dioxide to produce organic matter. It may be compared to the property which enables one animal to do more work than another animal of the same weight on a similar ration.

The removal from the ascending water current in the plant of substances derived from the soil is accomplished in the leaves. By the dissociation of these substances, ions are constantly furnished for metabolism into materials that may be built into the tissues of the plant. The remaining ions are kept in the solution. There is a constant tendency to bring the composition and density of the solution into equilibrium, by diffusion and osmosis, with the solution between the soil particle and the root-hair. The rapidity with which the metabolic process removes a substance from the solution in the plant, therefore, determines the rate at which it is removed from a solution of given composition and density in the soil. Plants making a rapid growth remove more nutrients in a given time than those making a slower growth, when the nutrient solution is of a given composition and density.

Another factor that affects the rate of absorption of salts from the soil is the solvent influence of exudates from the root-hairs. This subject has already been treated (pars. 321–326), and it only remains to be said that this action apparently varies with different kinds of plants, and probably accounts in no small measure for the difference in the ability of different plants to withdraw salts from the soil.

These several factors, which, when combined, deter-

mine the so-called "feeding power" of the plant, are recognized by the popular terms "weak feeder" and "strong feeder," — applied, on the one hand, to such crops as wheat or onions, which require very careful soil preparation and manuring, and, on the other hand, to maize, oats, or cabbage, which demand relatively less care. In the manuring and rotating of crops, this difference in absorptive power must be considered, in order not only to secure the maximum effect on the crop manured, but also to get the greatest residual effect of the manure on succeeding crops.

391. **The absorptive power of cereals.** — Cereals have the power of utilizing the potassium and phosphorus of the soil to a considerable degree, but they generally require fertilization with nitrogen salts. Most of the cereals, such as wheat, rye, oats, and barley, take up the principal part of their nitrogen early in the season, before the nitrification processes have been sufficiently operative to furnish a large supply of nitrogen; hence nitrogen is the fertilizer constituent that usually gives the best results, and should be added in a soluble form. Wheat, in particular, needs a large amount of soluble nitrogen early in its spring growth. Since it is a "delicate feeder," it does best after a cultivated crop or a fallow, by which the nitrogen has been converted into a soluble form. Oats can make better use of the soil fertility and do not require so much manuring. Maize is a very coarse "feeder," and, while it removes a large quantity of plant-food from the soil, it does not require that this shall be added in a soluble form. Farm manure and other slowly acting manures may well be applied for the maize crop. The long growing period required by the maize plant gives it opportunity to utilize the nitrogen as it becomes avail-

able during the summer, when ammonification and nitrification are active. Phosphorus is the substance usually most needed by maize.

332. The feeding of grass crops. — Grasses, when in meadow or in pasture, are greatly benefited by manures. They are less vigorous "feeders" than the cereals, have shorter roots, and, when left down for more than one year, the lack of aëration in the soil causes decomposition to decrease. There is usually a more active fixation of nitrogen in grass lands than in cultivated lands, but this becomes available very slowly.

Different soils and different climatic conditions necessitate different methods of manuring for grass. Farm manures may well be applied to meadows in all situations, while the use of nitrogen is generally profitable.

333. Leguminous crops. — Most of the leguminous crops are deep-rooted and are vigorous "feeders." Their ability to take nitrogen from the air makes the use of that fertilizer constituent unnecessary except in a few instances, such as young alfalfa on poor soil, where a small application of nitrate of soda is usually beneficial. Lime and potassium are the substances most beneficial to legumes on the majority of soils.

334. Root crops. — Many root crops will utilize very large quantities of plant-food if it is in a form in which they can use it. Phosphates and nitrogen are the substances generally required, the latter especially by beets and carrots.

335. Vegetables. — In growing vegetables, the object is to produce a rapid growth of leaves and stalks rather than seeds, and often this growth is made very early in the season. As a consequence, a soluble form of nitrogen is very desirable. Farm manure should also have a promi-

nent part in the treatment, as it keeps the soil in a mechanical condition favorable to retention of moisture, which vegetables require in large amounts, and it also supplies needed fertility. The very intensive method of culture employed in the production of vegetables necessitates the use of much greater quantities of manures than are used for field crops, and the great value of the product justifies the practice.

336. Fruits. — In manuring fruits, with the exception of some of the small, rapidly-growing ones, it is the aim to maintain a continuous supply of nutrients available to the plant, but not sufficient for stimulation except during the early life of the tree, when rapid growth of wood is desired. An acre of apple trees in bearing removes as much plant-food material from the soil in a season as does an acre of wheat. Farm manure and a complete fertilizer may be used, of which the constituents should be in a fairly available form, as a constant supply is necessary. A young growing orchard requires considerably more nitrogen than does an old orchard. Some nitrate of soda in early spring is desirable.

337. Mineral substances absorbed by plants. — The plant, in its process of growth, withdraws from the soil certain mineral substances that are presented to its roots in a dissolved condition. As the salts in solution are rather numerous, and since the diffusion by which the absorption is accomplished does not admit of the entire exclusion of any ion capable of diosmosis, there are to be found in the plant most of the mineral constituents of the soil. Some of these are concerned in the vital processes of the plant and are essential to its growth; others seem to have no specific function, but are generally present.

The substances commonly met with in the ash of plants

are potassium, sodium, calcium, magnesium, iron, manganese, aluminium, phosphorus, sulfur, silicon, and chlorine. In addition to these, nitrogen is absorbed from the soil in the form of soluble salts. Of these the substances known to be absolutely essential to the normal growth of plants to maturity, are potassium, calcium, magnesium, iron, phosphorus, sulfur, and nitrogen, while the others are probably beneficial to the plant in some way not yet discovered.

Of the substances acting as plant nutrients, each must be present in an amount sufficient to make possible the maximum growth consistent with other conditions, or the yield of the crop will be curtailed by its deficiency. To some extent certain essential substances may be replaced by others, as, for instance, potassium by sodium; but such substitution is probably possible only in some physiological rôle other than that of an elemental constituent of an organic compound. The substances that are likely to be so deficient in an available form in any soil as to curtail the yield of crops, are potassium, phosphorus, nitrogen, and possibly sulfur; while the addition of certain forms of calcium is likely to be beneficial because of its relation to other constituents and properties of the soil. It is for the purpose of supplying these substances, and to some extent to improve the mechanical condition of the soil, that mineral manures are used.

388. **Relation of plant growth to concentration of nutrient solution.** — It has already been stated that the addition of soluble salts to a soil has been found by some experimenters to apparently increase the concentration of the soil solution (par. 250). It has also been found that plant growth, as measured by weight of plants, increases with the concentration of the nutrient solution in

which the plants are grown.[1] This is the way in which it is generally believed that soluble fertilizer salts benefit plant growth. Insoluble plant-food materials have a similar, but less active, result because they do not increase the concentration of the soil solution to as great an extent.

339. Quantities of plant-food material removed by crops. — The utilization of mineral substances by crops is a source of loss of fertility to agricultural soils. In a state of nature, the loss in this way is comparatively small, as the native vegetation falls on the ground, and in the process of decomposition the ash is almost entirely returned to the soil. Under natural conditions, soil usually increases in fertility; for, while there is some loss through drainage and other sources, this is more than counterbalanced by the action of the natural agencies of disintegration and decomposition, and the fixation of atmospheric nitrogen affords a constant, though small, supply of that important soil ingredient.

When land is put under cultivation, a very different condition is presented. Crops are removed from the land, and only partially returned to it in manure or straw. This withdraws annually a certain small proportion of the total quantity of mineral substances, but, what is of more immediate importance, it withdraws all of this in a readily available form.

The following table, computed by Warington,[2] shows

[1] Hall, A. D., Brenchley, W. E., and Underwood, L. M. The Soil Solution and the Mineral Constituents of the Soil. Philosoph. Trans. Royal Soc. London, Series B, Vol. 204, pp. 179-200. 1913. Also, Lyon, T. L., and Bizzell, J. A. The Plant as an Indicator of the Relative Density of Soil Solutions. Proc. Am. Soc. Agron., Vol. 4, pp. 35-49. 1912.

[2] Warington, R. Chemistry of the Farm, pp. 64-65. London. 1894.

the quantities of nitrogen, potassium, phosphorus, and lime removed from an acre of soil by some of the common crops. The entire harvested crop is included:

Crop	Yield	Total Ash (Pounds)	Nitrogen N (Pounds)	Potash K_2O (Pounds)	Lime CaO (Pounds)	Phosphoric Acid P_2O_5 (Pounds)
Wheat	30 bushels	172	48	28.8	9.2	21.1
Barley	40 bushels	157	48	35.7	9.2	20.7
Oats	45 bushels	191	55	46.1	11.6	19.4
Maize	30 bushels	121	43	35.3	—	18.0
Meadow hay . .	$1\frac{1}{2}$ tons	203	49	50.9	32.1	12.3
Red clover . .	2 tons	258	102	83.4	90.1	24.9
Potatoes . . .	6 tons	127	47	76.5	3.4	21.5
Turnips . . .	17 tons	364	112	148.8	74.0	33.1

340. **Quantities of plant-food materials contained in soils.** — Comparing the figures given above with those showing the percentages of the fertilizing constituents in certain soils, it is evident that there is a supply in most arable soils that will afford nutriment for average crops for a very long period of time. (See pars. 46, 48, 52, 53.)

341. **Possible exhaustion of mineral nutrients.** — On the other hand, when it is considered that the soil must be depended upon to furnish food for humanity and domestic animals as long as they shall continue to inhabit the earth, at least so far as is now known, the very apparent possibility of exhausting, even in a period of several hundred years, the supply of plant nutrients becomes a matter of grave concern. The visible sources of supply, to replace or supplement those in the soils now cultivated, are, for the mineral substances, the subsoil and the natural deposits of phosphates, potash salts, and

limestone; and for nitrogen, deposits of nitrates, the by-product of coal distillation, and the nitrogen of the atmosphere. The last of these is inexhaustible, and the exhaustion of the nitrogen supply, which a few years ago was thought to be a matter of less than half a century, has now ceased to cause any apprehension. The conservation or extension of the supply of mineral nutrients is now of supreme importance. The utilization of city refuse and the discovery of new mineral deposits are developments well within the range of possibility, but neither of these promises to afford more than partial relief. The utilization of the subsoil through the gradual removal by natural agencies of the topsoil will, without doubt, tend to constantly renew the supply. The removal of topsoil by wind and erosion is, even on level land, a very considerable factor. The large amount of sediment carried in streams immediately after a rain, especially in summer, gives some idea of the extent of this shifting. This affects chiefly the surface soil, and thereby brings the subsoil into the range of root action.

There is little doubt that a moderate supply of plant-food materials will always be available in most soils, but for progressive agriculture manures must be used.

CHAPTER XX

ORGANISMS IN THE SOIL

A VAST number of organisms, animal and vegetable, live in the soil. By far the greater part of these belong to plant life, and these comprise the forms of greatest influence in producing the changes in structure and composition that contribute to soil productiveness. Most of the organisms are so minute as to be seen only by the aid of the microscope, while a much smaller proportion range from these to the size of the larger rodents. They may thus be classed as microörganisms and macroörganisms. The latter class will be considered first.

MACROÖRGANISMS OF THE SOIL

Of the macroörganisms in the soil the animal forms belong chiefly to (1) rodents, (2) worms, and (3) insects, and the plant forms to (1) the large fungi and (2) plant roots.

342. **Rodents.** — The burrowing habits of rodents — of which the ground squirrel, the mole, the gopher, and the prairie dog are familiar examples — result in the pulverization and transfer of very considerable quantities of soil. While the activities of these animals are often not favorable to agriculture, the effect on the character of the soil is rather beneficial and is analogous to that of good tillage. Their burrows also serve to aërate and drain the soil, and

in permanent pastures and meadows are of much value in this way.

348. Worms. — The common earthworm is the most conspicuous example of the benefit that may accrue from this form of life. Darwin, as the result of careful measurements, states that the quantity of soil passed through these creatures may, in a favorable soil in a humid climate, amount to ten tons of dry earth per acre annually. The earthworm obtains its nourishment from the organic matter of the soil, but takes into its alimentary canal the inorganic matter as well, expelling the latter in the form of casts after it has passed entirely through the body. The ejected material is to some extent disintegrated, and is in a flocculated condition. The holes left in the soil serve to increase aëration and drainage, and the movements of the worms bring about a notable transportation of lower soil to the surface, which aids still more in effecting aëration. Darwin's studies led him to state that from one-tenth to two-tenths of an inch of soil is yearly brought to the surface of land in which earthworms exist in normal numbers.

Instances are on record of land flooded for a considerable period so that the worms were destroyed, and the productiveness of the soil was seriously impaired until it was restocked with earthworms.

Wollny conducted experiments with soil, the soil in one case containing earthworms and in another case not containing them. Although there was much variation in his results, they were in every case in favor of the soil containing the worms, and in a number of the tests the yield on rich soil was several times as great as where no worms were present.

Earthworms naturally seek a heavy, compact soil, and

it is in soil of this character that they are most needed because of the stirring and aëration they accomplish. Sandy soil and the soils of arid regions, in which are found few or no earthworms, are not usually in need of their activities.

344. Insects. — There is a less definite, and probably less effective, action of a similar kind produced by insects. Ants, beetles, and the myriads of other burrowing insects and their larvæ effect a considerable movement of soil particles, with a consequent aëration of the soil. At the same time they incorporate into the soil a considerable quantity of organic matter.

345. Large fungi. — The larger fungi are chiefly concerned in bringing about the first stages in the decomposition of woody matter, which is disintegrated through the growth in its tissues of the root mycelia of the fungi. These break down the structure, and thus greatly facilitate the work of the decay bacteria. Action of this kind is largely confined to the forest and is not of great importance in cultivated soil.

Another function of the large fungi is exercised in the intimate, and possibly symbiotic, relation of the fungal hyphæ to the roots of many forest trees, in soil where nitrification proceeds very slowly, if at all, for nitrates are apparently not abundant in forest soils. This enveloping system of hyphæ, which may consist of masses in a definite zone of the cortex with occasional filaments passing outward into the soil, or which may surround the root with a dense mass of interwoven hyphæ, is called mycorrhiza.

The cereal, cruciferous, leguminous, and solanaceous plants are not associated with mycorrhiza. Mycotrophic plants are usually those that live in a humous soil filled

with the mycelia of fungi. It is thought that the mycorrhiza aid the higher plants to obtain nutriment that they must strive for in competition with the fungi.

Mycotrophic plants are also able to grow with a very small transpiration of moisture, as is well known to be the case with many conifers; and this restricted transpiration would doubtless result in lack of nutriment were it not for the assistance of the mycorrhiza.

346. Plant roots. — The roots of plants assist in promoting productiveness of the soil both by contributing organic matter and by leaving, on their decay, openings which render the soil more permeable to water and which also facilitate drainage and aëration. The dense mass of rootlets, with their minute hairs that are left in the soil after every harvest, furnish a well-distributed supply of organic manure, which is not confined to the furrow slice, as is artificially incorporated manure. The drainage and aëration of the lower soil, due to the openings left by the decomposed roots, are of the greatest importance in heavy soil, and the beneficial effects of clover and other deep-rooted plants are due in no small measure to this function.

MICROÖRGANISMS OF THE SOIL

FIG. 58. — Nematodes entering a plant root.

Of the microörganisms commonly existing in soils, the greater part belong to plant rather than to animal life. Of the latter, the only organisms of well-known economical importance are the nematodes (Fig. 58), whose injurious effect on plant growth is accomplished through the formation of galls on the roots, in which the young are hatched and live to sexual maturity.

347. Plant microörganisms. — The microscopic plants of the soil may be classed as slime molds, bacteria, fungi, and algæ.

348. Plant microörganisms injurious to higher plants. — Injurious plant microörganisms are confined mostly to fungi and bacteria. They may be entirely parasitic in their habits, or only partially so. They injure plants by attacking the roots. Those that attack other parts of plants may live in the soil during their spore stage, but they are not strictly microörganisms of the soil. Some of the more common diseases produced by soil organisms are: wilt of cotton, cowpeas, watermelon, flax, tobacco, tomatoes, and other plants; damping-off of a large number of plants; root-rot; galls.

These fungi or bacteria may live for long periods, probably indefinitely, in the soil, if the conditions necessary for their growth are maintained. Some of them will die within a few years if their host plants are not grown on the soil, but others are able to maintain existence on almost any organic substance. Once a soil is infected, it is likely to remain so for a long time, or indeed indefinitely. Infection is easily carried. Soil from infected fields may be carried on implements, plants, or rubbish of any kind, in soil used for inoculation of leguminous crops, or even in stable manure containing infected plants or in the feces resulting from the feeding of infected plants. Flooding of land by which soil is washed from one field to another may be a means of infection.

Prevention is the best defense from diseases produced by these soil organisms. Once disease has procured a foothold, it is practically impossible to eradicate all its organisms. Rotation of crops is effective for some diseases, but entire absence of the host crop is oftener neces-

sary. The use of lime is beneficial in the case of certain diseases. Chemicals of various kinds have been tried with little success. Steam sterilization is a practical method of treating greenhouse soils for a number of diseases. The breeding of plants immune to the disease affecting its particular species has been successfully carried out in the case of the cowpea and cotton plants, and can doubtless be accomplished with others.

In regions in which farming is confined largely to one crop or to a limited number of cereals, it is the common experience that yields decrease greatly in the course of a score of years after the virgin soil is broken. The cause for this is attributed by Bolley[1] in large measure to a diseased condition of the plants due to the growth of various fungi that inhabit the soil and attack the crops grown on it. He reports that he has experimented with pure cultures taken from wheat grains, straw, and roots, and has demonstrated that certain strains or species of Fusarium, Helminthosporium, Alternaria, Macrosporium, Colletotrichum, and Cephalothecium are directly capable of attacking and destroying growing plants of wheat, oats, barley, brome grass, and quack grass, and that within limits the disease may be transferred from one type of crop to another.

349. Plant microörganisms not injurious to higher plants. — The vegetable microörganisms of the soil all take an active part in removing dead plants and animals from the surface of the soil, and in bringing about the other operations that are necessary for the production of plants. The first step in the preparation for plant growth is to remove the remains of plants and animals that would

[1] Bolley, H. L. Wheat. North Dakota Agr. Exp. Sta., Bul. 107. 1913.

otherwise accumulate to the exclusion of other plants. These are decomposed through the action of organisms of various kinds, the intermediate and final products of decomposition assisting plant production by contributing nitrogen and certain mineral compounds that are a directly available source of plant nutriment, and also by the effect of certain of the decomposition products on the mineral substances of the soil, by which they are rendered soluble and hence available to the plant.

Through these operations the supply of carbon and nitrogen required for the production of organic matter is kept in circulation. The complex organic compounds in the bodies of dead plants or animals, in which condition plants cannot use them, are, under the action of microörganisms, converted by a number of stages into the very simple compounds used by plants. In the course of this process a part of the nitrogen is sometimes lost into the air by conversion into free nitrogen, but fortunately this may be recovered and even more nitrogen taken from the air by certain other organisms of the soil.

The slime molds, bacteria, fungi, and algae all play a part in these processes, but none of them so actively during every stage of the processes as do the bacteria. Molds and fungi are particularly active in the early stages of decomposition of both nitrogenous and non-nitrogenous organic matter. Molds are also capable of ammonifying proteins, and even re-forming the complex protein bodies from the nitrogen of ammonium salts. Certain of the molds and of the algae are apparently able to fix atmospheric nitrogen, and contribute a supply of carbohydrates required for the use of the nitrogen-fixing bacteria. Among these are *Aspergillus niger* and *Penicillium glaucum*.

It also seems probable that the fungi associated with

the roots of many forest trees and known as mycorrhizal fungi have the ability to fix atmospheric nitrogen, and that in some way the trees obtain a part, at least, of the nitrogen so fixed. The growth of forests on poor, sandy soil containing practically no nitrogen has been urged as an example of this process.

350. Bacteria. — Of the several forms of microörganisms found in the soil, bacteria are the most important. In fact, the abundant and continued growth of plants on the soil is absolutely dependent on the presence of bacteria, for through their action chemical changes are brought about which result in making soluble both organic and inorganic material necessary for the life of higher plants, and which, in part at least, would not otherwise occur.

FIG. 59. — Some types of soil microörganisms highly magnified. (a), nitrate formers; (b), nitrite formers; (c), B. graveolens; (d), B. fluorescens; (e), B. subtilis; (f), Clostridium pasteurianum.

Bacteria are thus transformers, not producers, of fertility in the soil, although, as will be seen later, certain kinds of bacteria take nitrogen from the air and leave it in the soil. With this exception, however, they add no plant-food to the soil. It is their action in rendering available to the plant material already present in the soil that constitutes their greatest present value in crop production. It is to their activity in conveying nitrogen from the air to the soil that we are indebted for most of our supply of nitrogen in virgin soils (see Fig. 59).

It is not usually the entire absence of bacteria from the soil that is to be avoided in practice, for all arable soils contain bacteria, although sometimes not all of the desirable forms; but, as great bacterial activity is required for the large production of crops, the practical problem is to maintain a condition of soil most favorable to such activity.

361. **Distribution of bacteria.** — Bacteria are found almost universally in soils, although they are much more numerous in some soils than in others. A number of investigators have stated that in soils from different localities and of different types that they have examined, the numbers of bacteria were proportional to the productiveness of the soils. The number of bacteria present has in some cases been shown to be proportional to the amount of humus contained in the soil. It is natural to expect that within certain limits both these findings will hold. The conditions obtaining in a productive soil are those favorable to the development of certain forms of bacteria, and these kinds constitute a very large proportion of those generally found in soils. However, there is evidence that comparatively unproductive soils may contain a large number of bacteria that are presumably not favorable to plant growth.

Samples of soil taken from certain productive and relatively unproductive parts of a field on the Cornell University farm contained a larger number of bacteria in the poor soil, although the two soils were equally well drained and the good soil had slightly more organic matter. They had also received practically the same treatment during the preceding few years: —

Character of soil	Number of bacteria per gram of dry soil
Good	1,200,000
Poor	1,600,000

After wheat had been growing for two months on these soils in the greenhouse, the soils being maintained at the same moisture content, the samples showed the following count: —

Character of soil	Number of bacteria to a gram of dry soil
Good	760,000
Poor	1,120,000

Another reason why this relation between the number of bacteria and soil productiveness does not hold is that the bacteria having the same functions in relation to plant-food do not always have the same physiological efficiency. In other words, they do not have the same virulence, a small number in some cases being able to bring about the same changes that in other cases require a much greater number.

Bacteria are found chiefly in the upper layers of soil, although not in large numbers at the immediate surface of the ground. In humid regions the layer between the first inch and the sixth or the seventh inch contains, in most soils, the great bulk of bacteria present. In arid or semiarid regions, bacteria are found at greater depths and the densest population is located at lower levels than in humid regions. This is largely because of the deeper penetration of the air and the conditions that accompany it.

352. Numbers of bacteria. — The number of bacteria in a soil will naturally vary with the conditions that favor or discourage their growth. In very sandy soils, forest soils, desert soils, water-logged soils, and soils low in humus, the bacteria are either absent or comparatively few in numbers. In soils very rich in organic matter, especially

place animal manure has been applied or where a carcass has been buried, the number becomes very large, as many as 100,000,000 to a gram of soil having been found, while in soil of ordinary fertility and tilth the numbers range from 1,000,000 to 5,000,000 to a gram. The extreme rapidity with which reproduction occurs makes it possible for the number to increase enormously when conditions are favorable for their growth.

The table on page 432 shows the number of bacteria to a gram of soil found in different parts of the United States during some portion of the growing season.

The figures showing the number of bacteria in each gram of soil that are presented in this table cannot be used for a comparison of the relative numbers of bacteria in soils of different regions of this country, because different methods were used by the experimenters in making the estimations. They are, however, an indication of what may be considered the ordinary range in arable soils.

308. **Numbers as influenced by season.** — It might be supposed that, like most plants, bacteria would develop most rapidly in summer months and that they would be found in largest numbers at that season, at least in regions of low temperatures during the winter months. That this is not always the case has been shown by Conn,[1] who found as the result of periodical enumeration of bacteria throughout a term of two years that the highest counts were obtained during the winter months, when the soil was frozen. This does not mean that all classes of bacteria are present in largest numbers at that season, but, as explained by Conn, it seems likely that certain

[1] Conn, H. J. Bacteria in Frozen Soils II. Centrlb. f. Bakt., II, Band 32, Seite 70-97. 1912.

NUMBER OF BACTERIA TO A GRAM OF SOIL DURING SOME PERIOD OF THE GROWING SEASON

STATE	SOIL	DEPTH	CROP	INVESTIGATOR	NUMBER OF BACTERIA
Delaware .	Stiff clay	3 inches	Orchard in high state of cultivation. In cover crops	Chester [1]	2,100,000
Delaware .	Adjoining soil above and of same character	3 inches	Meadow for twelve years	Chester [1]	450,000
Delaware .	Of same type as above	3 inches	Vegetables and heavily manured	Chester [1]	1,800,000
Delaware .	. . . .	. . .	Scarlet clover plowed under and after sale) with maize for ten years	Chester [1]	3,200,000
Kansas .	Loam, rich in humus	30 inches	Alfalfa, five years	Mayo and Kinsley [2]	10,500,000
Kansas .	Loam, richer in humus than soil above	30 inches	Alfalfa	Mayo and Kinsley [2]	28,960,000
Kansas .	Thin soil, gumbo mixed	30 inches	Mixed grasses	Mayo and Kinsley [2]	78,331
Kansas .	Loam, low in humus	30 inches	Oats and wheat	Mayo and Kinsley [2]	2,552,000
Iowa . .	Marshall loam, no lime applied	top soil	Oats	Brown [3]	1,630,000
Iowa	Marshall loam, 1,000 pounds lime per acre	top soil	Oats	Brown [3]	2,275,000
Iowa . .	Marshall loam, 2,000 pounds lime per acre	top soil	Oats	Brown [3]	2,780,000
Iowa . .	Marshall loam, 6,000 pounds lime per acre	top soil	Oats	Brown [3]	3,756,000

[1] Chester, F. D. The Bacteriological Analysis of Soils. Delaware Agr. Exp. Sta., Bul. 65. 1904.

[2] Mayo, N. S., and Kinsley, A. T. Bacteria of the Soil. Kansas Agr. Exp. Sta., Bul. 117. 1903.

[3] Brown, P. E. Some Bacterial Effects of Liming. Iowa Agr. Exp. Sta., Research Bul. 2. 1911.

forms predominate in summer and others in winter (see Fig. 90).

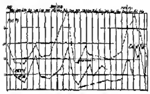

Fig. 90. — Periodical concentration of bacteria in soil of two plats during two years, expressed as millions to a gram of dry soil.

Brown and Smith[1] obtained results that in the main confirmed Conn's work, and they advanced the theory that the concentration of the soil solution immediately surrounding the soil particles, together with the high surface tension exerted by the soil particles, prevents the freezing of the surface film and that this water forms a suitable medium for the development of bacteria.

364. Conditions affecting growth. — Many conditions of the soil affect the growth of bacteria. Among the most important of these are the supply of oxygen and moisture, the temperature, the presence of organic matter, and the acidity or the basicity of the soil.

365. Oxygen. All soil bacteria require for their growth a certain amount of oxygen. Some bacteria, however, can continue their activities with much less oxygen than can others. Those requiring an abundant supply of oxygen have been called aërobic bacteria, while those preferring little or no air are designated as anaërobic

[1] Brown, P. E., and Smith, R. E. Bacterial Activities in Frozen Soil. Iowa Agr. Exp. Sta., Research Bul. 4. 1912.

bacteria. This is an important distinction, because those bacteria that are of the greatest benefit to the soil are, in the main, aërobes, and those that are injurious in their action are chiefly anaërobes. However, it seems likely that an aërobic bacterium may gradually accommodate itself within certain limits to an environment containing less oxygen, and an anaërobic bacterium may accommodate itself to the presence of a larger amount of oxygen. Thus a bacterium may be most active in the presence of an abundant supply of oxygen, but, when subjected to conditions in which the supply is small, growth continues but with lessened vigor. The term facultative bacteria has been used to designate those bacteria that are able to adapt themselves to considerable variation in oxygen supply. The structure, tilth, and drainage of the soil consequently determine largely whether aërobic or anaërobic bacteria shall be more active.

356. Moisture. — Bacteria require some moisture for their growth. A notable decrease in the moisture content of the soil may temporarily decrease the number of bacteria by limiting their development to the films of moisture surrounding the particles. With a decrease in the moisture content of a soil, there occurs an increase in the oxygen in the interstitial spaces. Those bacteria that thrive in the presence of oxygen are thereby favored, and the character of the bacterial flora is correspondingly changed. When the soil remains saturated, or nearly so, for any considerable period, the anaërobic forms assert themselves, and the usually beneficial activities of the aërobic bacteria are temporarily suspended. The most favorable moisture condition for the activity of the most desirable bacteria is that found in a well-drained soil.

357. **Temperature.** — Soil bacteria, like other plants, continue life and growth under a considerable range of temperature. Freezing, while rendering bacteria dormant, does not kill them, and growth begins slightly above that point. It has been shown that nitrification goes on at temperatures as low as from 37° to 39° F. It is not, however, until the temperature is considerably higher that their functions are pronounced. From 70° to 110° F. their activity is greatest, and it diminishes perceptibly below or above those points. The thermal death point of most forms of bacteria is found at some point between 110° and 160° F., but the spore forms even resist boiling. Only in some desert soils does the natural temperature reach a point sufficiently high to actually destroy bacteria, and there only near the surface. In fact, it is seldom that soil temperatures become sufficiently high to curtail bacterial activity.

358. **Organic matter.** — The presence of a certain amount of organic matter is essential to the growth of most, but not all, forms of soil bacteria. The organic matter of the soil, consisting as it does of the remains of a large variety of substances, furnishes a suitable food supply for a very great number of forms of organisms. The action of one set of bacteria on the cellular matter of plants embodied in the soil produces compounds suited to other forms, and so from one stage of decomposition to another this constantly changing material affords sustenance to a bacterial flora the extent and variety of which it is difficult to conceive. Not only do bacteria affect the organic matter of the soil, but, in the case of certain forms, their activities produce changes in the inorganic matter that cause it to become more soluble and more easily available to the plant.

A soil low in organic matter usually has a lower bacterial content than one containing a larger amount, and, under favorable conditions, the beneficial action, to a certain point at least, increases with the content of organic substance; but, as the products of bacterial life are generally injurious to the organisms producing them, such factors as the rate of aeration and the basicity of the soil must determine the effectiveness of the organic matter.

359. Soil acidity. — A soil having an acid reaction makes a poor medium for the growth of certain bacteria. A neutral or a slightly alkaline soil furnishes the most favorable condition for the development of the forms of bacteria most beneficial to arable land. The activities of many soil bacteria result in the formation of acids which are injurious to the bacteria themselves, and, unless there is present some basic substance with which these can combine, bacterial development is inhibited by their own products. This is one of the reasons why lime is so often of great benefit when applied to soils, and especially to those on which alfalfa and red clover are growing. For the same reason, the presence of lime hastens decay of organic matter in certain soils, and the conversion of nitrogenous material with a minimum loss into compounds available to the plants. As showing the value of lime in the process of nitrate formation, it has been pointed out that in the presence of an adequate supply of lime the availability of ammonium salts is almost as high as that of nitrate salts, but where the supply of lime is insufficient the value of ammonium salts is relatively rather low.

360. Functions of soil bacteria. — Bacteria have a part in many of the processes of the soil which greatly affects

its productiveness. It has become customary to refer to the changes produced by certain forms of bacteria as their function in contributing to soil productiveness.

361. **Decomposition of mineral matter.** — Certain bacteria decompose some of the mineral matter of the soil and render it more easily available to the plant. While the nature of the processes and their extent are not known, there is sufficient evidence to justify the above statement. It is well known that several forms of bacteria are instrumental in decomposing rock, and that sulfur and iron compounds are acted upon by other forms.

To what extent the very difficultly soluble forms of phosphorus, as tricalcium phosphate for example, are rendered soluble and available to agricultural plants by microörganisms, is a matter of great importance. The extent to which the subject has been investigated is rather limited, but, in the main, there is indicated a considerable action of both bacteria and fungi on tricalcium phosphate.

362. **Influence of certain bacteria and molds on the solubility of phosphates.** Some very significant experiments were performed by Stoklasa, Duchacek, and Pitra,[1] who found that bone meal, when brought into contact with pure cultures of certain bacteria, was apparently rendered soluble, the extent to which the solubility progressed varying with the different forms of bacteria brought into contact with it. The percentage of the total phosphorus in the meal that was rendered soluble was as follows: —

[1] Stoklasa, J., Duchacek, F., and Pitra, J. Über den Einfluss der Bakterien auf die Knochenzersetzung. Centrlb. f. Bakt., II, Band 6, Seite 526-535, 554-558. 1900.

	Per cent
Not inoculated	3.83
B. megatherium	21.56
B. fluorescens	9.19
B. proteus vulgaris	14.79
B. butyricus Hueppe	15.55
B. mycoides	23.08
B. mesentericus	20.60

Löhnis[1] quotes Grazia e Cerza to have found that *Aspergillus niger*, *Penicillium glaucum*, and *P. brevicaule*, isolated from garden soil, when placed in nutrient solution with tricalcium phosphate, assimilated one-fifth to one-third of the phosphorus in sixty days.

There is some difference of opinion whether the solvent action arising from bacterial growth is due entirely to the acids that are produced by the bacteria exerting such action, or whether there is also some other influence exercised by bacteria. Stoklasa accounts for the solvent action of the bacteria in his experiments by the bacterial secretion of proteolytic and diastatic enzymes acting on the bone meal. In opposition to this idea, Krober[2] maintains that the solvent action depends on the kind of fermentation that the organic matter undergoes, acid fermentation rendering the phosphates more soluble, while ammoniacal fermentation results in no solvent action on tricalcium phosphate and, in the presence of sufficient basic material, may render the monocalcium and dical-

[1] Löhnis, F. Handbuch d. Landw. Bakteriologie, Seite 701. Berlin. 1910.

[2] Krober, E. Über das Löslichwerden der Phosphorsäure aus Wasserunlöslichen Verbindungen unter der Einwirkung von Bakterien und Hefen. Jour. f. Landw., Band 57, Seite 5-80. 1909-1910.

cium phosphates insoluble. He would limit the solvent action of bacteria to the effect of the acids they produce.

Sackett, Patten, and Brown[1] have in a measure repeated Stoklasa's experiments and obtained somewhat similar results, which lead them to conclude that there is a solvent agent other than the acids produced by the bacteria.

It would appear from these experiments that bacteria, and possibly fungi, commonly found in soils act on tricalcium phosphate in such a manner as to render a part of it soluble. Nevertheless, experiments that have been conducted for the purpose of ascertaining whether tricalcium phosphate in soils is rendered more readily available to plants when large quantities of decomposing organic matter are present than when this is not the case, have not, in the main, indicated that the decomposing organic matter increases availability of the phosphorus (par. 439). An explanation of this may possibly be found in the occurrence of a reverse biological process which results in the transformation of soluble phosphates into insoluble ones, the occurrence of such a process having been found by Stoklasa[2] and others.

The carbon dioxide produced by bacteria is a solvent for many of the silicates of the soil, and may free calcium and potassium from hornblende and feldspar.

Various groups of sulfur bacteria, through the production of H_2S and H_2SO_4, act on iron in the soil and convert it into sulfide and sulfate. Carbon dioxide also

[1] Sackett, W. G., Patten, A. J., and Brown, C. W. The Solvent Action of Soil Bacteria upon the Insoluble Phosphates of Raw Bone Meal and Natural Rock Phosphate. Michigan Agr. Exp. Sta., Special Bul. 43. 1908.

[2] Stoklasa, J. Biochemischer Kreislauf des Phosphat-Ions im Boden. Centrlb. f. Bakt., II, Band 29, Seite 385–419. 1911.

plays a part in the solution of iron. The lower fungi and the algæ precipitate iron from solution as iron oxide.

365. Decomposition of non-nitrogenous organic matter. — The organic matter commonly decomposed in soils contains a large proportion of compounds containing no nitrogen. Many non-nitrogenous substances decompose rather rapidly, and the organic nitrogen disappears less rapidly than the carbon, hydrogen, and oxygen of organic bodies.

Humus always contains a higher percentage of nitrogen than do the plants from which it is formed.

The non-nitrogenous substances consist of cellulose and allied compounds forming the cell walls of plants, and the carbohydrates, organic acids, fats, and the like, contained in them. The dissolution of cellulose is brought about by the action of the enzyme cytase secreted by a number of fungi, and is also probably accomplished by the *Bacillus amylobacter*, but whether through the secretion of an enzyme is not known. Other bacteria have been reported to secrete a cytase that acts on certain constituents of the cell wall. It is probable that numerous organisms capable of fermenting cellulose and allied substances exist in the soil, accomplishing this decomposition through the production of cytase.[1]

The effect of cytase on cellulose and other fiber is to hydrolyse it with the formation of sugar, as glucose, mannose, xylose, arabinose, and the like.

Starch is converted into glucose by a ferment (diastase) either present in the plant itself or possibly secreted by fungi or bacteria. All the sugars are finally converted into organic acids which may combine with mineral bases. Distinct organisms have been isolated that can utilize for their development formates, acetates, propionates,

butyrates, and the like, the final product being carbon dioxide and water. Thus, step by step, the non-nitrogenous matter incorporated with the soil is carried by one and another form of organism from the most complex to the simplest combinations.

The final product of the decomposition of carbonaceous matter being carbon dioxide, there is a return to the air of the compound from which the carbon of the decomposing substance was originally derived. In the plant, unless it is saprophytic, the carbon of the tissues comes largely from the carbon dioxide of the air, from which more complex carbon-bearing compounds are produced and utilized in its functions or in its tissues. A portion of the carbon is returned to the air by the plant in the form of carbon dioxide; the remainder is retained by the plant, and may be returned by the process of decay or may be consumed by an animal, and, as the result of its physiological processes, either exhaled as carbon dioxide or deposited in the tissues to be later decomposed and converted into carbon dioxide. The soil is thus the scene of at least a part of the varied transformations through which carbon is continually passing as it is utilized by higher plants, animals, bacteria, and fungi.

The non-nitrogenous organic substances in their various stages furnish food for a large number of bacteria, among which are those concerned in the decomposition of mineral matter and in the processes of nitrification and nitrogen fixation. There are, therefore, two ways in which these substances are of great importance in soil fertility: (1) as a source of carbon dioxide and of organic acids; (2) as a food supply for useful soil bacteria.

361. **Decomposition of nitrogenous organic matter.** — The decomposition of nitrogenous organic matter is ac-

complished by a series of changes from one compound to another, as was seen to be the case with the non-nitrogenous materials. The final products are carbon dioxide, water, usually some hydrocarbon gases resulting from the carbon and hydrogen of the organic matter, and also some hydrogen sulfide or other gas containing sulfur or a final oxidation of the sulfur of the proteids into sulfates; while the nitrogen is ultimately converted into nitrates, or into free nitrogen, although a portion of the original nitrogen sometimes escapes into the air in the intermediate stage, ammonia.

The processes will be discussed under the following heads, which represent certain more or less definite stages in the decomposition: 1, decay and putrefaction; 2, ammonification; 3, nitrification; 4, denitrification; 5, fixation of atmospheric nitrogen. These various processes form what has been termed the nitrogen cycle.

CHAPTER XXI

THE NITROGEN CYCLE

Of the various elements composing the nutrients used by plants, nitrogen has the highest commercial value. It is, moreover, absorbed in large quantities by agricultural plants and the supply is constantly liable to loss in drainage water and in the gaseous form. Its importance to agriculture has led to much study of its occurrence, combinations, reactions, and movements in the soil.

When it is recalled that the nitrogen gas of the atmosphere is the one primitive source of the world's supply of nitrogen, it becomes apparent that the agencies that have been instrumental in its transfer from one condition to another have been extremely active. The movement of nitrogen from air to soil, from soil to plant, from plant back to soil or to animal, and from animal back to soil, with a return to air at various stages, involves many forces, many factors, many organisms, and many reactions.

366. **Decay and putrefaction.** — Decomposition of the nitrogenous organic matter of the soil, consisting largely of the proteins, begins with either one of two processes — decay or putrefaction. Decay is produced by aërobic bacteria, and naturally occurs when the conditions are most favorable for their development. When the conditions are otherwise, the growth of these bacteria is checked, and then further decomposition would be extremely slow

were it not for the other process — putrefaction. Putrefaction is produced by anaërobic bacteria. In the same body, and consequently in the same soil, decay and putrefaction may be in progress simultaneously, decay taking place on the outside and on the surfaces of other parts exposed to the air, while putrefaction occurs on the interior, where the supply of oxygen is limited. By means of the two processes, decomposition is greatly facilitated.

Decay (see Fig. 64) produces a very rapid and complete decomposition of the substance in which it operates, most of the carbon and hydrogen being quickly converted into carbon dioxide and water, and the nitrogen into ammonia and probably some free nitrogen. The latter is possibly due to the oxidation of ammonia, thus

$$4\ NH_3 + 3\ O_2 = 6\ H_2O + 2\ N_2$$

The sulfur of the proteins finally appears in the form of sulfates.

What the intermediate products are has not been determined, but in the decay of meat, in which there was an abundant supply of oxygen, succinic, palmytic, oleic, and phenyl-propionic acids have been found.

Putrefaction results in a large number of complex intermediate compounds and proceeds much more slowly. Many of the substances thus produced are highly poisonous, and most of them have a very offensive odor. They may be further broken down by decay when the conditions are suitable, or by a continuation of the process of putrefaction. In either case, the poisonous properties and the odor are removed.

In the process of decomposition of organic matter two classes of substances are produced: (1) those that have been excreted or secreted by the bacterium, and therefore

have passed through the metabolic processes of the organism; (2) those that have been formed because of the removal of certain atoms by bacteria or enzymes from compounds, thus necessitating a readjustment of the remaining atoms and the consequent formation of a new compound.

Putrefaction is carried on by a large number of forms of bacteria, the resulting products depending on the substance in process of decomposition and on the bacteria involved. Some of the characteristic, although not constant, products formed in the putrefaction of albumin and proteins are albumoses, peptones, and amino acids, followed by the formation of cadaverine, putrescine, skatol, and indol. Where an abundant supply of oxygen is present, or where a sufficient supply of carbohydrates exist, these substances are not formed. There are many other products of putrefaction, including a number of gases, as carbon dioxide, hydrogen sulfide, marsh gas, phosphine, hydrogen, nitrogen, and the like.

It will be noticed that these changes, like those occurring in the non-nitrogenous organic matter, involve a breaking-down of the more complex compounds and the formation of simpler ones; and that a very large number of bacteria are concerned in the various steps, while even the same substances may be decomposed and the same resulting compounds formed by a number of different species of bacteria.

Present-day knowledge of the subject does not make it possible to present a list of the bacteria concerned in each step, or to name all the intermediate products formed; but for the student of the soil the principal consideration is a knowledge of the circumstances under which the nitrogen is made available to plants, and the

conditions that are likely to result in its loss from the soil.

366. **Ammonification.** Decay and putrefaction may be considered as the beginning of the process of ammonification. Ammonification (see Fig. 61), as its name implies, is that stage of the process during which ammonia is formed from the intermediate products.

Like the other processes of decomposition, there are many species of bacteria capable of forming ammonia from nitrogenous organic substances. Different forms display different abilities in converting nitrogen of the same organic material into ammonia, some acting more rapidly or more thoroughly than others. In tests by certain investigators in which the same bacteria are used on different substances, the order of their efficiency is changed with the change of substance. It seems likely, therefore, that certain forms are most efficient when acting on certain organic compounds; that, in other words, each species is best adapted to the decomposition of certain substances, while capable of attacking others although less effectively. This characteristic preference of a class of bacteria for the decomposition of certain substances is made evident by the experiments of Sackett,[1] who found that in some soils dried blood was ammonified more rapidly than was cottonseed meal, while in other soils the reverse was true.

367. **Bacteria and substances concerned in ammonification.** — Among the bacteria producing ammonification are *B. mycoides*, *B. subtilis*, *B. mesentericus vulgatus*, *B. janthinus*, and *B. proteus vulgaris*. Of these, *B. mycoides* has been very carefully studied, and the

[1] Sackett, W. G. The Ammonifying Efficiency of Certain Colorado Soils. Colorado Agr. Exp. Sta., Bul. 184. 1912.

findings of Marchal[1] may be taken as representative of the process of ammonification. He found that when this bacterium was seeded on a neutral solution of albumin, ammonia and carbon dioxide were produced, together with small amounts of peptone, leucine, tyrosine, and formic, butyric, and propionic acids. He concludes that in the process, atmospheric oxygen is used, and that the carbon of the albumin is converted into carbon dioxide, the sulfur into sulfuric acid, and the hydrogen partly into water, and partly into ammonia by combining with the nitrogen of the organic substance. He suggests that a complete decomposition of the albumin occurs according to the following reaction:—

$$C_{72}H_{112}N_{18}SO_{22} + 77\,O_2 = 29\,H_2O + 72\,CO_2 + SO_3 + 18\,NH_3$$

The greatest activity occurred at a temperature of 86° F., and as low as 68° F. action was rather strong. Access of an increased amount of air, produced by increasing the surface of the liquid, increased the rate of ammonification. A slightly acid reaction in the liquid produced the maximum activity, but in a neutral or even slightly acid medium the process was continued, although much less actively.

Marchal found that *B. mycoides* was also capable of ammonifying casein, fibrin, legumin, glutin, myosin, serin, peptones, creatine, leucine, tyrosine, and asparagine, but not urea.

358. Nitrification. — Some agricultural plants can utilize ammonium salts as a source of nitrogen. This has

[1] Marchal, E. Sur la Production de l'Ammoniaque dans le Sol par les Microbes. Bulletin de l'Acad. Royale de Belg., 3 series, T. 25, pp. 727–776. 1893.

been determined for maize, rice, peas, barley, and potatoes. Other plants, such as beets, show a decided preference for nitrogen in the form of nitrates. Whether any of the common crops can thrive as well on ammonium salts as on nitrates has not been finally demonstrated. In most arable soils the transformation of nitrogen does not stop with its conversion into ammonia, but goes on by an oxidation process to the formation of first nitrous, and then nitric, acids (see Fig. 61). This may be considered to proceed according to the following equations:—

$$2\,NH_3 + 3\,O_2 = 2\,HNO_2 + 2\,H_2O$$
$$2\,HNO_2 + O_2 = 2\,HNO_3$$

The acid in either case combines with one of the bases of the soil, usually calcium, so that calcium nitrate results.

Each of these steps is brought about by a distinct bacterium, but the bacteria are closely related. Collectively they are called nitrobacteria. Nitrosomonas and Nitrosococcus are the bacteria concerned in the conversion of ammonia into nitrous acid or nitrites. The former are supposed to be characteristic of European, and the latter of American, soils. They are sometimes referred to as nitrous ferments.

Nitrobacter are those bacteria that convert nitrites into nitrates. They are also designated nitric ferments. There seem to be some differences in bacteria from different soils, but the differences are slight and the conditions favoring the actions of the bacteria are similar. It is also true that the conditions favoring the action of Nitrosomonas and Nitrobacter are similar, and they are generally found in the same soils, although some

experiments show that in the same soil nitrites may sometimes accumulate, indicating conditions more favorable to the development of the Nitrosomonas bacteria.

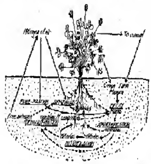

FIG. 111. — Diagrammatic representation of the movements of nitrogen between soil, plant, animal, and atmosphere. This has been termed the nitrogen cycle.

The formation of nitrates usually follows closely on the production of nitrites, so that there is rarely more than a trace of the latter to be found in soils. A soil favorable to the process of nitrification is usually well adapted to all the processes of nitrogen transformation.

Marked differences have been found in the nitrifying power of bacteria from different soils. Highly productive soils have generally been found to contain bacteria having greater nitrifying efficiency than those from less productive soils, but this may not always be the case, as other factors may limit the productiveness.

368. **Effect of organic matter on nitrification.** — A peculiarity in the artificial culture of nitrifying bacteria

is that they cannot be grown in artificial media containing organic matter. This property for a long time prevented the isolation and identification of these organisms, as it was hardly conceivable that organisms living in the dark, where energy cannot be obtained from sunlight, could exist without using the energy stored by organic matter. It has been suggested, in explanation of this, that the energy produced by the oxidation involved in the process of nitrification makes possible the growth of the organisms under these apparently impossible conditions. Some experimenters report having grown nitrobacteria in organic media, but it is generally believed at present that this is not possible and that there has been some error in the work of these experimenters.

The presence of peptone in the proportion of 600 parts per million completely prevents the development of nitrobacteria, and one-half that quantity checks it, while 150 parts of ammonia to the million has a similar effect. In a normal soil the quantity of soluble ammonium salts is well below this amount, as must also be that of soluble organic matter. In confirmation of the inhibiting effect of organic matter on the nitrobacteria, cases have been reported of soils very rich in organic matter in which no bacteria of this type exist.

It has also been stated that very heavy manuring with organic manures results in decreased nitrification in the soil. While this may be true where farm manure is used in the quantities sometimes applied in gardening operations, it is not likely to be the case in soils on which ordinary field crops are grown. The principle is well illustrated by the dry-earth closet. Manure mixed with earth in relatively small proportions and kept aërated by occasional mixing undergoes a very thorough decompo-

position of the manure but without any corresponding increase in nitrates. On the other hand, under field conditions, manure used in relatively small amounts does not undergo this serious loss.

The application of twenty tons of farm manure to the acre to soil on a clay loam soil for three consecutive years, at Cornell University, resulted in a larger production of nitrates on the manured soil than on a contiguous plat of similar soil left unmanured. This was true during the third year of the applications, when the land was in sod, and also during the fourth year, when no manure was applied to either plat and when both plats were planted to corn, as may be seen from the following table:

NITRATES PRODUCED ON HEAVILY MANURED AND ON UNMANURED SOIL

	Nitrates in Parts to a Million, Dry Soil	
	Unmanured soil	Twenty tons manure to the acre for three years
Land in timothy		
April 23	8.2	21.0
May 3	4.1	4.6
May 14	3.3	4.5
May 30	2.0	4.0
June 1	2.4	2.0
June 13	0.8	1.1
June 20	1.3	3.0
July 24	3.2	2.8
August 14	1.8	3.0
Land in maize		
May 19	17.5	30.1
June 22	43.8	79.3
July 6	60.0	105.0
July 28	105.0	304.0
August 10	151.0	184.0

370. **Effect of soil aëration on nitrification.** — Probably the most potent factor governing nitrification in the soil is the supply of air. In clay, and even in loam soils, the tendency to compactness is such as to prevent the presence of sufficient air to enable nitrification to proceed as rapidly as desirable unless the soil is well tilled. Columns of soil eight inches in diameter and eight inches in depth were removed from a field of clay loam on the Cornell University farm, and carried to the greenhouse without disturbing the structure of the soil as it existed in the field. At the same time, vessels of similar size were filled with soil dug from a spot near by. These may be termed unaërated and aërated soils. Both were kept at the same temperature and moisture content in the greenhouse, but no plants were grown on them. The production of nitrates was as follows: —

Time of Analysis	Nitrates in Dry Soil, Parts to the Million	
	Unaërated soil	Aërated soil
When taken from field	3.2	3.2
After standing one month	4.2	17.6
After standing two months	11.0	45.6

371. **Effect of sod on nitrification.** — Nitrification proceeds slowly on sod land, especially if the soil is heavy. On the same type of soil as that used in the experiment last described, the average quantities of nitrates for each month of the growing season in the surface eight inches of sod land, as compared with maize land under the same planting, were as follows: —

Month	Nitrates in Dry Soil, Parts to the Million	
	Sod land	Maize land
April	3.9	—
May	3.0	17.1
June	3.4	40.2
July	4.0	104.0
August	5.4	186.7

The amount of nitrogen removed by the maize crop was greater than that removed by the timothy; consequently the greater amount in the former soil cannot be due to the effect of the crop.

So far as the conservation of nitrogen is concerned, sod is an ideal crop, for nitrates are formed very little faster than they are used, and are not carried off in large quantities by the drainage water.

In the corn land as much as 175 pounds of nitrate nitrogen was present in the first twelve inches of one acre, or fully three times as much as was used by the crop.

372. **Depths at which nitrification takes place.** — Warington[1] concluded from his experiments that nitrification takes place only in the surface six feet of soil. Hall[2] has pointed to the fact that no more nitrates were leached from the 60-inch lysimeter at Rothamsted than from the one 40 inches deep; which is very good evidence that in

[1] Warington, R. On the Distribution of the Nitrifying Organism in the Soil. Trans. Chem. Soc., Vol. 51, p. 118. 1887.

[2] Hall, A. D. The Book of the Rothamsted Experiments, p. 230. New York, 1905.

that particular soil nitrification does not take place below 40 inches from the surface. In more porous soils, however, nitrification probably extends deeper, especially in the rich and porous subsoils of arid and semiarid regions.

In all probability, nitrification is largely confined to the furrow slice, where the opening-up of the soil by tillage has provided the necessary air, and where the temperature rises to a point more favorable to the action of nitrifying bacteria. The results from the aërated and unaërated soils as shown above represent the differences that doubtless exist between the furrow slice and the subsoil so far as nitrification is concerned.

373. Loss of nitrates from the soil. — Nitrogen having been converted into the form of nitric acid, it immediately combines with available bases in the soil, forming salts, all of which are very easily soluble and which are carried in solution by the soil water. In a region of much rainfall, the removal of nitrates in the drainage water is very rapid. Hall[1] states that nitrates formed during the summer or the autumn of one year are practically all removed from the soil of the Rothamsted fields before the crops of the following year have advanced sufficiently to utilize them. It was formerly customary to fertilize with ammonium salts in autumn, but the drainage water showed on analysis such a large quantity of nitrates during the months intervening between the time of fertilizing and the opening of the growing season that the practice was discontinued.

In regions of less rainfall or of greater surface evaporation, the loss in this way is less, reaching a minimum in an arid region when irrigation is not practiced. Under

[1] Hall, A. D. The Soil, p. 178. New York, 1903.

such conditions, there is a return of nitrates to the upper soil as capillary water moves upward to replace evaporated water. In fact, wherever evaporation takes place to any considerable extent there is some movement of this kind. The need for catch crops to take up and preserve nitrogen is therefore greater in a humid region than in an arid or a semiarid one. A system of cropping that allows the land to stand idle for some time, or a crop that requires intertillage, as does maize, fails to utilize all the nitrates produced, and promotes the loss of nitrogen in drainage water.

374. Nitrate reduction. — The nitrogen-transforming bacteria thus far studied have been those that cause the oxidation of nitrogen as the result of their activities. A number of forms of bacteria that accomplish a reverse action may now be considered. The several processes involved are commonly designated by the general term denitrification, and comprise the following: 1, reduction of nitrates to nitrites and ammonia; 2, reduction of nitrates to nitrites, and of these to elementary nitrogen.

The number of organisms that possess the ability to accomplish one or more of these processes is very large — in fact, greater than the number involved in the oxidation processes; but, in spite of their numbers, permanent loss of nitrogen in ordinary arable soils is unimportant in amount, although in heaps of barnyard manure it may be a very serious cause of loss.

Some of the specific bacteria reported as bringing about nitrate reduction are: *B. ramosus* and *B. pestifer*, which reduce nitrates; *B. mycoides*, *B. subtilis*, *B. mesentericus vulgatus*, and many other ammonification bacteria which are capable of converting nitrates into ammonia.

B. denitrificans alpha and *B. denitrificans beta* reduce nitrates with the evolution of gaseous nitrogen.

375. Nitrate-assimilating organisms. — In addition to the nitrate-reducing bacteria already mentioned, there are other bacteria which also utilize nitrates; but, like higher plants, these convert the nitrogen into organic nitrogenous substances. However, as they operate in the dark and cannot obtain energy from sunlight, they must have organic acids or carbohydrates as a source of energy. While these bacteria cannot be considered as nitrate reducers, they help to deplete the supply of nitrates when conditions are favorable for their development. What these conditions are is not well understood, nor can any estimate be made as to the extent of their operations.

376. Denitrification. The term denitrification may be used to include both the process of nitrate reduction and that of nitrate assimilation (see Fig. 61).

Most of the denitrifying bacteria perform their functions only under a limited amount of oxygen, while others can operate in the presence of a more liberal supply, but, in general, thorough aëration of the soil practically prevents denitrification. Straw apparently carries an abundant supply of denitrifying organisms, and also furnishes a supply of carbohydrates which favor their action; so that stable manure is very likely to undergo denitrification, and straw or coarse stable manure are conducive to the growth of denitrifying bacteria in the soil.

Under ordinary farm conditions, denitrification is of no significance in the soil where proper drainage and good tillage are practiced. Warington[1] showed that if

[1] Warington, R. Investigations at Rothamsted Experimental Station. U. S. D. A., Office of Exp. Sta., Bul. 8, p. 68. 1892.

an arable soil is kept saturated with water to the exclusion of air, nitrates added to the soil are decomposed, with the evolution of nitrogen gas. As lack of drainage is usually most pronounced in early spring, when the soil is likely to be depleted of nitrates, it is not likely that much loss arises in this way unless a nitrate fertilizer has been added. Among the many difficulties arising from poor drainage, denitrification of an expensive fertilizer may be a very considerable item.

The addition of a nitrate fertilizer to a well-drained soil receiving stable manure is not likely to result in a loss of nitrates unless the dressings of manure have been extremely heavy. Hall[1] states that at Rothamsted, where large quantities of nitrate of soda are used every year in connection with annual dressings of farm manure, the nitrate produces nearly as large an increase when added to the manured as when added to the unmanured plat. In other words, there appears to be no loss of nitrate by denitrification.

It is possible to reach a point in manuring at which denitrification may take place. Market-gardeners sometimes reach this point, when fifty tons or more of farm manure, in addition to a nitrate fertilizer, are added to the soil. Plowing under heavy crops of green manure may produce the same result. In either case, the best way to overcome the difficulty is to allow the organic matter to partly decompose before adding the fertilizer. The removal of the easily decomposable carbohydrates needed by the denitrifying organisms decreases or precludes their activity.

377. Nitrogen fixation through symbiosis with higher plants. — It has long been recognized by farmers that

[1] Hall, A. D. The Book of the Rothamsted Experiments, pp. 114–115. New York, 1905.

certain crops, as clover, alfalfa, peas, beans, and some others, improve the soil, making it possible to grow larger crops of cereals after those crops have been on the land. Within the past century the benefit has been traced to an increase in the nitrogen content of the soil, and the specific plants so affecting the soil were found to be, with a few exceptions, those belonging to the family of legumes. It has furthermore been demonstrated that under certain conditions these plants utilize the uncombined nitrogen of the atmosphere (see Fig. 61), and that they contain, both in the aërial portions and in the roots, a very high percentage of nitrogen. In consequence, the decomposition of even the roots of the plants in the soil leaves a large amount of nitrogenous matter.

378. **Relation of bacteria to nodules on roots.** — It has also been shown that the utilization of atmospheric nitrogen is accomplished through the aid of certain bacteria that live in nodules (tubercles) on the roots of the plants. These bacteria take free nitrogen from the air in the soil, and the host plant secures it in some form from the bacteria or their products. The presence of a certain species of bacteria is necessary for the formation of tubercles. Leguminous plants grown in cultures or in soil not containing the necessary bacteria do not form nodules and do not utilize atmospheric nitrogen, the result being that the crop produced is less in amount and the percentage of nitrogen in the crop is less than if nodules were formed.

The nodules are not normally a part of leguminous plants, but are evidently caused by some irritation of the root surface, much as a gall is caused to develop on a leaf or a branch of a tree by an insect. In a culture containing the proper bacteria, the prick of a needle on the root surface will cause a nodule to form in the course of a few

days. The entrance of the organism is effected through a root-hair which it penetrates, and it may be seen as a filament extending the entire length of the hair and into the cells of the cortex of the root, where the growth of the tubercle starts.

Even where the causative bacteria occur in cultures or in the soil, a leguminous plant may not secure any atmospheric nitrogen, or perhaps only a small quantity, if there is an abundant supply of readily available combined nitrogen on which the plant may draw. The bacteria have the ability to utilize combined nitrogen as well as uncombined nitrogen, and prefer to have it in the former condition. On soils rich in nitrogen, legumes may therefore add little or no nitrogen to the soil; while in properly inoculated soils deficient in nitrogen an important gain of nitrogen results.

While *B. radicicola* is considered the organism common to all leguminous plants, it is now known that the organisms from one species of legume are not equally well adapted to the production of tubercles on each of the other species of legumes. They show greater activity on some species than on others, but do not develop so successfully on all species as on the one from which the organisms were taken. It was rather generally believed at one time that the longer any species of legume is in contact with the organisms from another species, the more active this species becomes and the greater is the utilization of atmospheric nitrogen. Considerable doubt has been cast on this view in recent years, and it is now generally conceded that the bacteria of certain legumes are not capable of inoculating certain other species of legumes.

379. Transfer of nitrogen to the plant. — It has been shown by several investigators that bacteria from the

nodules of legumes are able to fix atmospheric nitrogen even when not associated with leguminous plants. There would seem to be no doubt, therefore, that the fixation of nitrogen in the tubercles of legumes is accomplished directly by this organism, not by the plant itself nor through any combination of the plant and the organism — though both of these hypotheses have been advanced. The part played by the plant is doubtless to furnish the carbohydrates which are required in large quantities by all nitrogen-fixing organisms and which the legumes are able to supply in large amounts. The utilization of large quantities of carbohydrates by the nitrogen-fixing bacteria in the tubercles may also account for the small proportion of non-nitrogenous organic matter in the plants.

How the plant absorbs this nitrogen after it has been secured by the bacteria is less well understood. Early in the growth of the tubercle, a mucilaginous substance is produced, which permeates the tissues of the plant in the form of long, slender threads containing the bacteria. These threads develop by branching or budding, and form what have been called Y and T forms, known as bacteroids, which are peculiar to these bacteria. The threads finally disappear, and the bacteria diffuse themselves more or less through the tissues of the root. What part the bacteroids play in the transfer of nitrogen is not known. It has been suggested that in this form the nitrogen is absorbed by the tissues of the plant. It seems quite likely that the nitrogen compounds produced within the bacteria cells are diffused through the cell wall and absorbed by the plant.

330. **Soil inoculation for legumes.** — Immediately following the discovery of the nitrogen-fixing bacteria, the possibility was conceived of securing a better growth of

leguminous crops on soils not having previously grown such crops successfully. Extensive experiments showed the practicability of inoculating land for a certain leguminous crop by spreading on its surface soil from a field on which the same crop is successfully growing. It is manifestly much better to apply the organisms from a certain species of legumes from a field having grown the same species, than to attempt to use organisms from another species of legumes. The fact that soil inoculation by means of soil from other fields may possibly transmit weed seeds and fungous diseases, and also necessitates the transportation of a great bulk and weight of material, has led to numerous efforts to inoculate soil by means of pure cultures. The pure culture may also make it possible to bring to the soil bacteria of greater physiological efficiency than those already there.

The first attempt at inoculation by pure cultures was made in Germany, the cultures being sold under the name of "nitragin." Careful experiments made with this material previous to the year 1900 did not show it to be very efficient; but in recent years improvements in the method of manipulating the cultures have resulted in much greater success. In "nitragin" the medium used for growing the organisms is gelatin, and before use this was formerly dissolved in water; but now a solution of greater density is used in order to prevent a change of osmotic pressure, which may cause plasmolysis and result in the destruction of the bacteria.

Within recent years a number of cultures for soil inoculation have been offered to the public. The first of these utilized absorbent cotton to transmit the bacteria in a dry state from the pure culture in the laboratory to the user of the culture, who was to prepare therefrom

mother culture to be used for inoculating the soil. Careful investigation of this method showed that its weakness lay in drying the cultures on the absorbent cotton, which frequently resulted in the death of the organisms. More recently, liquid cultures have been placed on the market in this country, and these have, in the main, proved to be more successful, notably those sent out by the United States Department of Agriculture. Another very successful culture medium, now being distributed by the Department of Plant Physiology at Cornell University, is steamed soil. The process of steaming under a pressure of two or three atmospheres increases greatly the solubility of both organic and inorganic matter, and produces a medium highly favorable to the development of the organisms isolated from the nodules of legumes.

Liquid cultures for legume inoculation have now been prepared and distributed by the United States Department of Agriculture for seven years, and during this time a record has been kept of the results so far as it has been possible to do this. These are summarized by Kellerman[1] as follows: average percentage of success, 76; average percentage of failure, 24. If, however, the doubtful reports are included with the failures, the percentage of success is reduced to 38. Kellerman states as his opinion that inoculation with pure liquid cultures is as certain a means of infection as is inoculation with soil from fields on which legumes have been successfully grown for extended periods, if the soil to be infected is one well adapted to the leguminous crop; but on soils not well suited to legumes, the use of soil from old fields is a much more satisfactory medium with which to attempt inocula-

[1] Kellerman, K. F. The Present Status of Soil Inoculation. Centrlb. f. Bakt., II, Band 34, Seite 42–50. 1912.

tion. It is only a question of time until a successful method of inoculating soil from artificial cultures will be found. In the meantime, inoculation by means of infested soil is the most practical method.

361. Nitrogen fixation without symbiosis with higher plants. — If a soil is allowed to stand idle, either without vegetation or in grass, it will, under favorable moisture conditions in the northern states, accumulate in one or two years an appreciable amount of nitrogen not present at the beginning of the period. At the Rothamsted Experiment Station, one of the fields in volunteer plants, consisting mainly of grass without legumes, gained in the course of twenty years about twenty-five pounds of nitrogen per acre annually.[1] According to Hall, the nitrogen brought down by rain would account for about five pounds to the acre per annum, and dust, bird droppings, and the like, for a little more.

362. Nitrogen-fixing organisms. — Direct experiment has shown that certain bacteria have the ability to utilize atmospheric nitrogen and to leave it in the soil in a combined form (see Fig. 81). An anaërobic bacillus, — *Clostridium pastorianum* — was first found to produce this result. Later, a commercial culture called "alinit" was placed on the market in Germany, claimed to contain *Bacterium ellenbachensis*, with which the soil was to be inoculated, and it was claimed that a large fixation of atmospheric nitrogen would result. A number of tests of this material failed to show that it caused any marked fixation of atmospheric nitrogen.

A number of other nitrogen-fixing organisms have since been discovered. There are: (1) several members

[1] Hall, A. D. On the Accumulation of Fertility by Land Allowed to Run Wild. Jour. Agr. Sci., Vol. 1, p. 241. 1905.

of the group designated Azotobacter, which are aërobic bacteria, and which some investigators hold to be capable of fixing atmospheric nitrogen when grown in pure cultures, while others believe them to be able to do so, at least in large amounts, only in the presence of certain other organisms; (2) members of the Granulobacter group, which are large spore-bearing bacilli of anaërobic habits; (3) *Bacillus radiobacter*, which appear to be closely related to or identical with the *B. radicicola* of legume tubercles. The last-named has been shown to be able to fix atmospheric nitrogen even when not growing in symbiosis with legumes.

There are doubtless many other nitrogen-fixing organisms still to be discovered.

A peculiarity of these nitrogen-fixing organisms is their use of carbohydrates, which they decompose in the process of nitrogen fixation. They secure more atmospheric nitrogen when in a nitrogen-free medium. The presence of soluble lime or magnesium salts, especially carbonates, is necessary for the best performance of the nitrogen-fixing function, as is also the presence of a somewhat easily soluble form of phosphorus. The organisms are exceedingly sensitive to an acid condition of the soil.

383. Mixed cultures of nitrogen-fixing organisms. Mixed cultures of the various organisms mentioned fix larger amounts of nitrogen than do the pure cultures of any one of them, while some forms are incapable of fixing nitrogen in pure cultures. Certain algæ, particularly the blue-green algæ, aid greatly in promoting growth and nitrogen fixation by these organisms. This they probably do by producing carbohydrates, which are used by the bacteria as a source of energy for nitrogen fixation, the bacteria furnishing the algæ with nitrogenous compounds.

To what extent the relation is symbiotic is not known at present, but it seems probable that a relation may exist similar to that between leguminous plants and the nitrogen-gathering bacteria in their nodules.

384. Nitrogen fixation and denitrification antagonistic. — Nitrogen fixation and denitrification are reverse processes. The former is, for most bacteria, favored by an abundant supply of air and a moderately high temperature. Thus, at 75° F. fixation was rapid, at 59° F. it was decreased, and at 44° F. there was no fixation. Denitrification is favored by a somewhat limited supply of oxygen.

There is no reason to believe that the practical importance of nitrogen fixation without legumes is equal, under the most favorable conditions, to that with legumes. A further knowledge of the organisms effecting fixation and of their habits will doubtless make possible a greater utilization of their powers to supplement the use of legumes as a source of combined nitrogen in the soil.

TREATMENT OF SOILS WITH VOLATILE ANTISEPTICS AND WITH HEAT

Attention was first drawn to the effects of carbon bisulfide on the soil in a paper by Girard[1] and one by Oberlin[2] which appeared in 1894. Girard noticed that soil treated with carbon disulfide for the purpose of combating a parasitic disease of sugar-beet was more productive than it

[1] Girard, A. Recherches sur l'Augmentation des Récoltes par l'Injection dans le Sol du Sulfure de Carbone à Doses Massives. Bul. Soc. Nationale d'Agric., Tome 54, p. 356. 1894.
[2] Oberlin. Bodenmüdigkeit und Schwefelkohlenstoff. Mainz, 1894.

was before such treatment. The beneficial effect of the treatment extended to the second year.

Oberlin found a somewhat similar condition where the soil of vineyards treated with carbon bisulfide to kill phylloxera showed greatly increased productiveness after the treatment. The effect of carbon bisulfide on the vineyard soil was to make it possible to raise grapes continually on the same land, whereas it had previously been necessary to rest the land by growing a succession of other crops at intervals of several years. It was noticed, however, that immediately after treatment the plants did not grow so well as under normal conditions. Systematic investigations of the subject then began, and as early as 1895 Pagnoul[1] reported that when carbon bisulfide is applied to soils nitrification is temporarily depressed.

Investigation of the effect of heat on soil had begun somewhat earlier, when Frank[2] showed in 1888 that it increases the quantities of soluble matter, both organic and inorganic, as well as causing the soil to be more productive.

The subject has been investigated by a large number of persons, and in addition to carbon bisulfide a considerable number of other volatile antiseptics, including ether, chloroform, and toluene, have been found to influence the productiveness of soils. The effect of heat, particularly in steam, at various temperatures from slightly above normal to more than 200° C., has also been studied, while

[1] Pagnoul, M. Nouvelles Recherches sur les Transformations que Subit l'Azote dans le Sol. Annales Agronomiques, Tome 21, pp. 497-501. 1895.

[2] Frank, B. Ueber den Einfluss welchen das Sterilisiren des Erdbodens auf die Pflanzen-Entwickelung ausübt. Ber. d. Deut. Bot. Gesell. (Generalversammlungs Heft) Band 6, Seite 87-98. 1888.

it has been found that the mere drying of soils effects important changes in their solubility and in the bacterial processes that occur in them. As the result of the investigations, certain well-established facts have been worked out in connection with certain treatments when applied to most soils.

385. Effects of carbon bisulfide and heat on properties of soils. — Volatile antiseptics usually increase the productiveness of soils, although there may be at first a slight temporary retardation of plant growth. It is of course necessary to permit the antiseptic to volatilize from the soil before seed is planted. For this purpose the soil is spread out in a thin layer, in which condition it is allowed to remain until the odor of the antiseptic has disappeared. The soil is then placed in vessels and moistened and the seeds are planted in it.

Other characteristic effects of treatment with volatile antiseptics reported by different investigators are: (1) an initial decrease in the numbers of bacteria, followed by a long-continued increase; (2) a disturbance of the equilibrium of the flora, by which certain bacteria multiply more rapidly than others; (3) a slight initial increase in ammonia content, followed by a considerable increase in the rate of production of ammonia; (4) depression of the process by which ammonia is converted into nitric acid, and a very slow recovery in the activity of the bacteria concerned, as a result of which ammonia accumulates in the soil; (5) an increase in the rate at which oxidation takes place in soils; (6) destruction of protozoa.

386. Hypotheses to account for effects of carbon bisulfide and of heat. — A number of hypotheses have been formulated by which to account for the increased plant growth and for changes induced in soils by treat-

ment with heat and volatile antiseptics. A number of these theories will be mentioned, but it should be remembered that much important work on the subject has been done by investigators who have not advanced any hypotheses.

367. Koch's theory. — Koch[1] was the first to offer any explanation. In 1899 he stated it as his opinion that carbon bisulfide has a directly stimulating action on the plants themselves. He later[2] found ether to have a similar action, and continued his experiments with carbon bisulfide. He found that soil sterilized with heat produced better crops when treated with carbon bisulfide than when not so treated, and concludes that the effect of the antiseptic, therefore, cannot be due to the effect of the antiseptic on bacteria. He also experimented with field soils, and showed that the size of the crop on treated soils is not proportional to the quantity of nitrogen contained.

The theory of Koch has been supported by Fred,[3] who fertilized soils with an abundant supply of sodium nitrate and found that in every case in which carbon bisulfide was added the growth and yield of crop were much superior to those in the corresponding pots not treated with that substance. He concludes that as there was no lack of plant-food and other conditions favorable to plant

[1] Koch, A. Untersuchungen über die Ursachen der Rebenmüdigkeit mit besonderer Berücksichtigung der Schwefelkohlenstoffbehandlung. Arb. Deut. Landw. Gesell., Heft 40, Seite 7-38. 1899.

[2] Koch, A. Ueber die Wirkung von Aether und Schwefelkohlenstoff auf Höhere und Niedere Pflanzen. Centralb. f. Bakt., II, Band 31, Seite 175-185. 1911-1912.

[3] Fred, E. B. Effect of Fresh and Well-rotted Manure on Plant Growth. Virginia Poly. Inst. Agr. Exp. Sta., Ann. Rept. 1909-1910, pp. 148-159.

growth, the effect of the antiseptic must have been directly on the plants.

388. **Hiltner and Störmer's theory.** — According to Hiltner and Störmer,[1] the effect of treatment with carbon bisulfide is to cause a disturbance in the equilibrium of the different forms of soil bacteria. These investigators compared the numbers in three groups of bacteria that developed on gelatin plates inoculated from soil infusions. The groups were Streptothrix, liquefiers, and non-liquefiers. The normal relation of these in the soil with which they worked was 30 per cent Streptothrix, 5 per cent liquefiers, and 70 per cent non-liquefiers. After treatment with carbon bisulfide the relative proportions were 5 per cent, 10 per cent, and 85 per cent, respectively. From 70 to 75 per cent of the whole number of bacteria were destroyed by the treatment, but the numbers rapidly increased after treatment, rising in a few weeks to 50,000,000 to a gram in a soil that contained 10,000,000 to a gram before treatment. This increase is due largely to the development of the non-liquefiers, the Streptothrix remaining at about the same actual number.

The fact that the equilibrium of the bacterial flora was so greatly disturbed by the treatment with carbon bisulfide led Hiltner and Störmer to believe that the greater productiveness of the soil after treatment is due to the greater effectiveness of the surviving and rapidly developing forms in rendering available the supply of plant

[1] Hiltner, L., and Störmer, K. Studien über die Bakterienflora des Ackerbodens, mit besonderer Berücksichtigung ihres Verhaltens nach einer Behandlung mit Schwefelkohlenstoff und nach Brache. Arb. Biol. Abt. f. Land- u. Forstwirtschaft am Kaiserl. Ges. Amt, Band III, Heft 5. Berlin, 1903. Abstract in Centrlb. f. Agrikultur Chemie, 33 Jahrg., Seite 361-364. 1904.

nutrients in the soil, and to a decrease in the number of denitrifying bacteria, which obviates loss of available nitrogen through their action.

Heinze,[1] working with soils treated with carbon bisulfide, and Pfeiffer, Frank, Friedlander, and Ehrenberg,[2] working with steamed soils, found that there was a large fixation of nitrogen following these treatments. They conclude that this is at least partly responsible for the greater productiveness of the soils after the treatments mentioned.

389. Russell and Hutchinson's theory. — The next comprehensive theory to be brought forward was one by Russell and Hutchinson, who account for the increased productiveness of soils partially sterilized, either by heat or by volatile antiseptics, as due to the use by plants of the ammonia, which, as had been shown by previous investigators, accumulated in soils so treated by reason of the stimulation given to the process of ammonification and the depression of nitrification. They hold, furthermore, that the stimulation of ammonification is brought about by the greatly increased numbers of bacteria in the soil following the destruction of some larger organisms, probably protozoa or allied forms, that normally interfere with the activities of the ammonifying bacteria. Careful experiments by these investigators have shown that there is a much larger quantity of nitrogen in the combined forms of ammonia and nitrates in partially sterilized

[1] Heinze, B. Eine Weitere Mitteilungen über den Schwefelkohlenstoff und die CS_2-Behandlung des Bodens. Centralb. f. Bakt., II, Band 18, Seite 56-74, 246-264, 462-470, 624-634, 790-798. 1907.

[2] Pfeiffer, Th., Frank, L., Friedlander, K., and Ehrenberg, P. Der Stickstoffhaushalt des Ackerbodens. Mitt. d. Landw. Inst. d. Königl. Univ. Breslau, Band 4, Seite 715-851. 1909.

soils than in untreated soils. There can be no doubt, therefore, that, at least for some higher plants, the quantity of available nitrogen is greater in the treated soils.

The relation of protozoa to the ammonifying bacteria is somewhat more difficult of demonstration. Methods for the enumeration of protozoa in the soil are not sufficiently well worked out to admit of an entirely satisfactory study of their relation to the ammonifying bacteria. However, Russell and Hutchinson do not hold that protozoa are necessarily the limiting factor in ammonia production in normal soils, but grant that some other organism of comparatively large size may be responsible for this. They intimate also that not only the available nitrogen, but also the quantities of other plant nutrients, are limited by organisms destroyed by partial sterilization; otherwise increased productiveness induced by partial sterilization would be confined to soils in which nitrogen is normally the limiting factor. The theory does imply, however, that plant-food is the limiting factor in all soils benefited by partial sterilization under the conditions of the experiment.[3]

[3] Russell, E. J., and Darbishire, F. V. Oxidation in soils and its relation to productiveness. Part 2. The influence of partial sterilization. Jour. Agr. Sci., Vol. 2, pp. 305–326. 1907.

Russell, E. J., and Hutchinson, H. B. The effect of partial sterilization of soil on the production of plant food. Jour. Agr. Sci., Vol. 3, pp. 111–144. 1909.

Russell, E. J., and Hutchinson, H. B. The effect of partial sterilization of soil on the production of plant food. Part 2.

Russell, E. J., and Hutchinson, H. B. The limitation of bacterial numbers in normal soils and its consequences. Jour. Agr. Sci., Vol. 5, pp. 152–221. 1913.

Buddin, W. Partial sterilization of soil by volatile and non-volatile antiseptics. Jour. Agr. Sci., Vol. 6, pp. 417–451. 1914.

Some typical results of investigations by Russell and Hutchinson on the effect of partial sterilization on bacteria numbers, ammonia production, and presence of protozoa are given below:—

	Bacteria after ... Days, per Gram of Dry Soil	Nitrogen as NH_3 and NO_3 after ... Days, Parts per Million of Dry Soil	[illegible]	Protozoa Found
Untreated soil . .	11,100,000	18.0	Present	Ciliates Amœbæ Monads
Soil heated to 40° C. for three hours	7,500,000	14.4	Present	Ciliates Amœbæ Monads
Soil heated to 56° C. for three hours	37,500,000	36.7	Killed	All killed

390. Greig-Smith's theory. — An entirely different explanation of the effect of partial sterilization on soils has been advanced by Greig-Smith.[1] He states that when disinfectants are applied to the soil their action is a double one. They kill the less resistant bacteria, and dissolve from the surfaces of the soil particles a waxy covering, to which he has given the name "agricere." The surviving bacteria, among which are the beneficial ones, are able to develop more rapidly because of the greater accessibility of the food supply which the removal of the "agricere" has exposed.

Greig-Smith holds that heat destroys substances toxic

[1] Greig-Smith, R. The Bacteriotoxins and the "Agricere" of Soils. Centralb. f. Bakt., II, Band 30, Seite 154–156. 1911.

to bacteria, and also certain of the less resistant bacteria, thus permitting the more resistant species to multiply very rapidly owing to the absence of the bacteriotoxins.

In order to ascertain whether chloroform has any effect other than the destruction of protozoa, Greig-Smith applied it to soil previously heated to 62° C. (which he had found was sufficient to kill all protozoa), and then determined the number of bacteria in untreated soil, in heated soil, and in soil heated and treated with chloroform. The counts to a gram of soil were made at intervals, and are shown below:[1]—

	At Start	3 Days	10 Days	20 Days	30 Days
Untreated soil	50	880,000	2,700,000	4,300,000	4,400,000
Soil heated at 62° C.	16	15,800,000	11,800,000	9,000,000	8,000,000
Soil heated at 62° C. and treated with chloroform	13	24,600,000	45,400,000	41,600,000	90,800,000

Greig-Smith concludes that as the bacteria developed more rapidly in the soil treated with chloroform after heating than in the soil which was only heated and in which the protozoa were presumably dead, the chloroform must have exerted some beneficial effect other than the destruction of protozoa, and assumes that this is due to the removal of "agricere."

Partial or complete sterilization of soils has been prac-

[1] Greig-Smith, R. Contributions to our Knowledge of Soil Fertility. Proc. Linnean Soc. New South Wales, 1913, Part II, pp. 238-243.

tised in greenhouses for a long time, principally for the purpose of combating plant diseases. Its value in increasing productiveness has been a consideration since this phase of the subject has been emphasized by investigations, and the treatment of "sewage-sick" soils has been shown by Russell and Golding[1] to be a practical matter. It is as a means of studying the principles of soil fertility, however, that the investigation of the subject of partial sterilization of the soil is of greatest importance.

[1]Russell, E. J., and Golding, J. Investigations on "sickness" in soil. Part 1. "Sewage sickness." Jour. Agr. Sci., Vol. 5, pp. 27-47. 1912.

Russell, E. J., and Golding, J. Investigations on "sickness" in soil. Part 2. "Sickness" in glasshouse soils. Jour. Agr. Sci., Vol. 5, pp. 86-111. 1912.

CHAPTER XXII

THE SOIL AIR

The air of the soil is merely a continuation of the atmospheric air into the interstitial spaces of the soil, when these are not filled with water. As it is more or less inclosed by the soil, movement does not take place so readily as it does above the surface of the ground and hence the soil air is more greatly influenced by its surroundings than is atmospheric air. This leads to important differences in composition between the atmospheric air and soil air, the composition of the latter depending on a variety of conditions in which physical, chemical, and biological properties play a part.

FACTORS THAT DETERMINE VOLUME

The amount of air that soils contain varies with their properties, and in any one soil the air content varies with certain changes to which the soil is subject from time to time. The factors that influence the volume of air in soils are: (1) texture; (2) structure; (3) organic matter; (4) moisture content.

302. Texture. — The size of the soil particles affects the air capacity of the soil in exactly the same way as it does the pore space, since in dry soil they are identical. A fine-textured soil in a dry condition would therefore contain as large a volume of air as would a

coarse-textured soil, provided the particles were spherical and all of the same size. Under the conditions actually existing in the field, the soils composed of small particles generally possess the larger amount of air space.

392. Structure. — The volume of air in a water-free soil being identical with the pore space, the formation of aggregates of particles is favorable to a large air volume. The volume of air in any soil, therefore, changes from time to time; and particularly is this true of a fine-grained soil, in which the changes in structure are greater than in a soil with large particles. A change in soil structure may greatly alter the volume of air contained by changing the pore space, thereby influencing the productiveness. Clay is affected to the greatest extent in this way.

393. Organic matter. — Since organic matter is more porous than mineral particles of any size or arrangement, the effect of that constituent is always to increase the volume of air. While this is generally beneficial in a humid region, it is often very injurious in an arid region. Unless sufficient water falls on the soil to wash the soil particles around the organic matter and to maintain a supply sufficient to promote decomposition, the presence of vegetable matter leaves the soil so open that the capillary rise of moisture is interfered with, and the considerable movement of air keeps the soil dry, with the result that the portion of the soil layer mixed with and lying above the organic matter is too dry to germinate seeds or to support plant growth.

394. Moisture content. — It is quite evident that the larger the proportion of the interstitial space filled with water, the smaller will be the quantity of air contained. This does not necessarily mean that the higher the per-

centage of water in the soil, the smaller will be the volume of air, since the amount of pore space determines both the water and the air capacity. A soil with 30 per cent moisture may contain more air than one with a water content of 20 per cent, because of the tendency of moisture to move the soil particles farther apart.

In soils in the field, the average diameter of the cross section of the pore space is the most potent factor in determining the volume of air. Small spaces are likely to hold water, while larger spaces, not retaining water against gravity, are filled with air.

In a clay soil the volume of air is increased, other things being equal, by the formation of granules, and is decreased by deflocculation or compaction. The volume of air in any soil may be calculated from the following formula: —

$$\%\text{ air space} = \%\text{ pore space} - (\%\ H_2O \times \text{app. sp. gr.})$$

COMPOSITION OF SOIL AIR

The air of the soil differs from that of the outside atmosphere in that it contains more water vapor, a much larger proportion of carbon dioxide, a correspondingly smaller amount of oxygen, and slightly larger quantities of other gases, including ammonia, methane, hydrogen sulfide, and the like, formed by the decomposition of organic matter.

396. Analyses of soil air. — The composition of the air of several soils, as determined by Boussingault and Lewy, is quoted by Johnson[1] in the table following: —

[1] Johnson, S. W. How Crops Feed, p. 218. New York, 1891.

Character of Soil	Volume in One Acre of Soil to Depth of 14 Inches		Composition of 100 Parts of Soil Air by Volume		
	Air (Cu. ft.)	Carbon Dioxide (Cu. ft.)	Carbon Dioxide	Oxygen	Nitrogen
Sandy subsoil of forest .	4,416	14	0.24	—	.
Loamy subsoil of forest .	3,530	28	0.79	19.66	79.55
Surface soil of forest . .	5,891	57	0.87	19.61	79.52
Clay soil	10,310	71	0.66	19.99	79.35
Soil of asparagus bed not manured for one year .	11,182	86	0.74	19.02	80.24
Soil of asparagus bed freshly manured . .	11,182	172	1.54	18.80	79.66
Sandy soil, six days after manuring . . .	11,783	257	2.21	—	—
Sandy soil, ten days after manuring (three days of rain)	11,758	1,144	9.74	10.35	79.91
Vegetable mold compost	21,049	772	3.64	16.45	79.91

There are several factors that influence the composition of the soil air, those of greatest importance being the production and escape of carbon dioxide.

296. Sources of carbon dioxide in soil air. The presence of carbon dioxide in soils is due in small part to infiltration from the atmospheric air, there being a tendency for the carbon dioxide, which is heavier than oxygen and nitrogen, to settle out. It may also have a purely chemical origin. But in much greater measure is the carbon dioxide a product of biological processes that occur in the soil. At one time it was believed that the formation of carbon dioxide in soils was a purely chemical process of oxidation, and possibly a part of the gas is formed in that way. It has already been seen that there is a condensation of gases in the manifold pores

of the soil (see par. 268), the organic portion of which is especially capable of condensing gases. Oxygen condensed on the surface of this organic matter would, in the words of Johnson,[1] "spend itself in chemical action," of which carbon dioxide would be the result.

There is now no doubt, however, that biological processes are largely responsible for the occurrence of the large quantity of carbon dioxide in the soil air. There are two distinct processes involved: (1) the physiological action of bacteria by which they absorb oxygen and give off carbon dioxide, and (2) the excretion of carbon dioxide by plant roots. The extent to which carbon dioxide is produced in normal soils in these two ways has been estimated by Stoklasa,[2] who has done much work on the subject. He concludes that the microörganisms in an acre of soil to a depth of four feet may produce between sixty-five and seventy pounds of carbon dioxide a day for two hundred days in the year, and that during the growing period the roots of oats or wheat would give off nearly as much to an acre.

327. Production of carbon dioxide as affecting composition. — Although the formation of carbon dioxide in the soil depends on the decomposition of organic matter, it is not always proportional to the quantity of organic matter present. The rate of decomposition varies greatly, and where this is depressed, as is sometimes seen in muck or forest soils, the content of carbon dioxide is relatively low. A high percentage of organic matter

[1] Johnson, S. W. How Crops Feed, p. 218. New York, 1891.

[2] Stoklasa, J. Ueber den Ursprung die Menge und die Bedeutung des Kohlendioxids im Boden. Centrlb. f. Bakt., II, Band 14, Seite 723–736. 1905.

is in itself likely to prevent a proportional formation of carbon dioxide, since the accumulation of the gas may inhibit further activity of the decomposing organisms.

Ramann[1] states that the percentage of carbon dioxide in the soil air has the following relations: —

1. The carbon dioxide increases with the depth.

2. In general the percentage of carbon dioxide rises and falls with the temperature, being higher in the warm months and lower in the cold months.

3. Changes in temperature and air pressure change the percentage of carbon dioxide.

4. In the same soil the content of carbon dioxide varies greatly from year to year.

5. An increase of moisture in the soil increases the percentage of carbon dioxide.

6. The amount of carbon dioxide varies in different parts of the soil.

The movement of carbon dioxide from the soil depends chiefly on diffusion into the outside atmosphere. The conditions governing diffusion, which will be discussed elsewhere (par. 400), therefore largely determine the rate of loss of carbon dioxide from the soil.

FUNCTIONS OF THE SOIL AIR

Both oxygen and carbon dioxide, as they exist in the air of the soil, have important relations to the processes by which the soil is maintained in a habitable condition for the roots of plants. Deprived of these gases, the soil would soon become sterile.

398. Oxygen. — An all-important process in the soil is that of oxidation, because by it the organic matter

[1] Ramann, E. Bodenkunde. Seite 301. Berlin, 1905.

that would soon accumulate to the exclusion of higher plant life is disposed of, and the plant-food materials are brought into a condition in which they may be absorbed by plant roots. The presence of oxygen is essential to the life of the decomposing organisms and to the complete decay of organic matter. Through this process, roots of past crops, as well as other organic matter that has been plowed under, are removed from the soil. The process of decay gives rise to products, chiefly carbon dioxide, that are solvents of mineral matter, and leaves the nitrogen and ash constituents more or less available for plant use.

Oxygen is also necessary for the germination of seeds and the growth of plant roots. These phenomena, although not involving the removal of large quantities of oxygen, are yet entirely dependent on its presence in considerable amounts.

393. Carbon dioxide. — The solvent action of carbon dioxide is its most important function in the soil. By this action it prepares for absorption by plant roots most of the mineral substances found in the soil. Although a weak acid when dissolved in water, its universal presence and continuous formation during the growing season results in a large total effect.

Carbonic acid dissolves from the soil more or less of all the nutrients required by plants. The amounts so dissolved are appreciably greater than those dissolved in pure water. The constant formation of carbon dioxide by decomposition of organic matter keeps this solvent continually in contact with the soil.

Carbon dioxide serves a useful purpose in combining with certain bases to form compounds beneficial to the soil. Particularly is this the case with calcium carbonate,

which is of the greatest benefit to the soil in maintaining a slight alkalinity very favorable to the development of many beneficial bacteria and to the maintenance of good tilth.

Stoklasa[1] has correlated the carbon dioxide production with the quantity of phosphates found in the drainage water from certain soils. Some of his results are given below: —

	P_2O_5 in Drainage Water (Kilograms to a hectare)	Relative Production of CO_2 (Milligrams to a kilogram soil in 24 hours)
Loam	5.2	24
Clay	3.5	15
Lime soil	5.8	36
Humous soil	8.4	56

Stoklasa considers that the production of carbon dioxide is a measure of the intensity of bacterial action in the soil, and that in consequence of this activity the phosphorus is rendered soluble.

When carbon dioxide is combined as sodium carbonate or potassium carbonate in considerable quantity, as in certain alkali soils, a very injurious action on plant roots and on soil structure results. On plants the carbonate acts as a direct poison (see par. 306). The effect on soil structure is to deflocculate the particles producing the separate grain or the compact arrangement (see par. 130).

[1] Stoklasa, J. Methoden zur Bestimmung der Atmungsintensität der Bakterien im Boden. Zeit. f. d. landw. Versuchswesen in Oesterreich, Band 14, Seite 1243–79. 1911.

MOVEMENT OF SOIL AIR

There is a constant movement of the air in the interstitial spaces of the soil and an exchange of gases between the soil atmosphere and the outside atmosphere, as well as a more general, but probably less effective, movement of the air out of or into the soil, as the controlling conditions may determine. The movement may be produced by any one or more of the following phenomena: (1) diffusion of gases; (2) movement of water; (3) changes in atmospheric pressure; (4) changes of temperature in atmosphere or in soil; (5) suction produced by wind.

400. **Diffusion of gases.** — The wide difference in the composition of soil and atmospheric air gives rise to a movement of gases due to a tendency for the external and the internal gases to come into equilibrium. According to Buckingham,[1] the interchange of atmospheric and soil air is due in large measure to diffusion.

The rate of movement of the soil air due to diffusion is dependent on the aggregate volume of the interstitial spaces, not on their average size. Thus, it is the porosity of the soil that influences most largely the diffusion of the air from it. Consequently the size of the particles is not a factor, but good tilth permits diffusion to take place more rapidly than does a compact condition of soil, as the volume of the pore space is thereby increased. Compacting the soil in any way, as by rolling or tramping, has the opposite effect.

401. **Movement of water.** — As water, when present in a soil, fills certain of the interstitial spaces, it decreases the air space when it enters the soil and increases it when

[1] Buckingham, E. Contributions to Our Knowledge of the Aeration of Soils. U. S. D. A., Bur. Soils, Bul. 25. 1904.

it leaves. The downward movement of rain water produces a movement of soil air by forcing it out through the drainage channel below, while at the same time a fresh supply of air is drawn in behind the wave of saturation as the water passes down from the surface. The movement thus occasioned extends to a depth where the soil becomes permanently saturated with water. Twenty-five per cent of the air in a soil may be driven out by a normal change in the moisture content of the soil.

402. Changes in atmospheric pressure. — Waves of high or of low atmospheric pressure, frequently involving a change of 0.5 inch on the mercury gauge, cross the continent alternately every few days. The presence of a low pressure allows the soil air to expand and issue from the soil, while a high pressure following causes the outside air to enter in order to equalize the pressure. An appreciable, but not important, movement of soil air is produced in this way.

The size of the interstitial spaces is more potent than their volume in effecting soil ventilation by this and the following methods.

403. Changes of temperature in atmosphere or in soil. A movement of soil air may be induced by a change of temperature in the atmosphere or in the soil itself. Changes in atmospheric temperature act in the same way as do changes in atmospheric pressure; in fact, it is the effect of temperature on air pressure that causes the movement. Like the movement due to atmospheric pressure, it is not great; but where the soil immediately at the surface of the ground attains a temperature of 120° F. at midday, as is the case in the Corn Belt, the movement must be appreciable.

The diurnal change in soil temperature decreases

rapidly from the surface downward, due to the absorption and slow conduction of heat (see par. 227). At the Nebraska Experiment Station[1] the average diurnal range for the month of August, 1901, was as follows: —

DIURNAL RANGE OF AIR AND SOIL TEMPERATURES

	Degrees Fahrenheit
Air 6 feet above ground	14.4
Soil 1 inch below surface	37.0
Soil 3 inches below surface	14.8
Soil 6 inches below surface	9.2
Soil 9 inches below surface	6.6
Soil 12 inches below surface	4.3
Soil 24 inches below surface	0.5
Soil 36 inches below surface	0.0

This soil contains about fifty per cent of pore space, in the upper foot of which forty per cent is normally filled with water during the summer months. This leaves 518 cubic inches of air in the upper cubic foot of soil. With an increase in temperature, the air expands $\frac{1}{491}$ in volume for each degree Fahrenheit. The average increase of temperature is, in this case, about 11 degrees Fahrenheit for the first foot. The air exhaled or inhaled by each cubic foot of soil would then be

$$\frac{518 \times 11}{491} = 11.6 \text{ cubic inches}$$

As this is slightly over two per cent of the air contained in the upper foot of soil, and as the movement below that depth is negligible, the change in composition at any

[1] Sweezy, G. D. Soil Temperatures at Lincoln, Nebraska. Neb. Agr. Exp. Sta., 16th Ann. Rept., pp. 95-102. 1903.

one time is not great; but this pumping effect is kept up day after day, although less energetically in the cooler seasons of the year. In proportion as poor drainage equalizes the temperature it would prevent this type of circulation. The total effect, assisted by diffusion, is to aid materially in ventilating the soil. Owing to diffusion of air in the interstitial spaces, the air expelled is different in composition from that inhaled.

404. Suction produced by wind. — The movement of wind, being almost always in gusts, alternately increases and decreases the atmospheric pressure at the surface of the soil. There is a tendency, therefore, for the soil air to escape and for atmospheric air to penetrate the soil with each change in pressure. The effect presumably influences only the superficial air spaces, but it must be very frequent in its action. No measurements have been made and no definite estimate of its effect can be stated.

METHODS FOR MODIFYING THE VOLUME AND THE MOVEMENT OF SOIL AIR

The conditions that influence the ventilation of soils are: (1) volume and size of the interstitial spaces; (2) moisture content; (3) daily and annual range in temperature.

Although the size of the interstitial spaces does not appear to greatly influence the diffusion of gases from a soil, it has a marked effect on certain of the other processes by which air enters and leaves the soil. A sandy soil, a soil in good tilth, and, particularly, a soil composed of clods, permit of more rapid movement of air than does a compact soil.

While a certain movement of air through the soil is desirable, and indeed necessary, for the reasons already stated a very considerable movement is injurious unless there is an abundant rainfall. The effect of air movement through the soil is to remove soil moisture. In a region of light rainfall and low atmospheric humidity, this may be disastrous if the soil is not kept compact by careful tillage. On the other hand, in a humid region and in clay soil there is likely to be too small a supply of oxygen for the use of crops and lower plant life unless the soil is well stirred.

406. Tillage. — The ordinary operations of tillage greatly influence the ventilation of the soil. When a soil is plowed, the soil at the bottom of the furrow is exposed directly to the air at the surface, and, by the separation of adhering particles and aggregates of particles, air is brought into contact with particles that may previously have been completely shut off from air. It is partly because of its effect on soil ventilation that plowing is beneficial, and the necessity for its practice is greater in a humid region and on a heavy soil than in a region of light rainfall and on a light soil. The practice of listing corn, by which the soil is sometimes left unplowed for a number of years, although in semiarid regions productive of crops of sufficient yield to make them profitable, would fail utterly on the heavy soils of a humid region.

Subsoiling, by loosening the subsoil, increases the ventilation to a greater depth. Rolling and subsurface packing both diminish the volume and the movement of air. Their essential difference is in their effect on moisture rather than on air. Harrowing and cultivation have the opposite effect, and both increase the production of nitrates in the soil by promoting aeration.

406. Manures. — Farm manures, lime, and those amendments that improve the structure of the soil, have for that reason a beneficial action on soil aëration. By their effect on the physical condition of the soil they increase its permeability, and by their action in contributing to the production of carbon dioxide they stimulate diffusion.

It is chiefly through its effect in increasing the volume of air space in soils that farm manure is injurious in light soils of semiarid regions. It may thus be injurious instead of beneficial, if used under certain conditions.

407. Underdrainage. By lowering the water table, underdrainage by means of tiles removes from the soil the water from all but the small capillary spaces, and leaves free to the air the remainder of the interstitial spaces. There is also a very considerable movement of air through the drains, and a movement of air upward from the drains to the surface of the soil, which serves to aërate to some extent this intervening layer. The aëration of the soil brought about by underdrainage is one of its beneficial features.

408. Irrigation. The influence of irrigation on the soil is much like that of rainfall. The alternate filling and emptying of the interstitial spaces with water and air causes a very considerable change of air.

409. Cropping. — The roots of plants left in the soil after a crop has been harvested decay and leave channels in the soil through which air penetrates. Below the furrow slice, where the soil is not stirred and where it is usually more dense than at the surface, this affords an important means of aëration. The absorption of moisture from the soil by roots also causes the air to penetrate, in order to replace the water withdrawn.

CHAPTER XXIII

COMMERCIAL FERTILIZERS

As treated in this volume, manures include all those substances, with the exception of water (the function and application of which is discussed in par. 167), that are added to soils to make them more productive. There are several ways in which manures applied to soils may increase plant growth: (1) by addition of the nutrient materials utilized by plants, which is the chief function of most of the so-called commercial fertilizers; (2) by improvement of the physical condition of a soil, which usually results from the application of lime and the incorporation of organic matter; (3) by favoring the action of useful bacteria, which is one of the beneficial results of farm manure and also of lime; (4) by counteracting the effects of toxic substances — as, for instance, the conversion of sodium carbonate into sulfate by gypsum, or the neutralization of acidity, or possibly the destruction of toxic organic substances by certain salts; (5) by catalytic action, either on chemical processes in the soil or by its influence on those bacteria that exert a favorable influence on soil fertility or by direct stimulation of the plant.

410. Early ideas of the function of manures.— Manures were at one time supposed to pulverize the soil, and the French word *manœuvrer*, from which the word manure comes, implies to work with the hand. This

idea probably originated through the observation that farm manure, which was the only manure in use at that time, made the soil less cloddy.

It has been argued, notably by Jethro Tull,[1] that since tillage pulverizes the soil it may be used as a substitute for manures. There are, however, conditions aside from tilth that are influenced by manures, and good tilth alone will not suffice to maintain a permanently intensive agriculture. It is true in the United States, as it is in Europe, that a large consumption of manures goes hand in hand with a highly developed and intensive system of farming.

411. Development of the idea of the nutrient function of manures. — While the use of animal excrement on cultivated soils was practiced as far back as systematic agriculture can be definitely traced, the earliest record of the use of mineral salts for increasing the yield of crops was published in 1669 by Sir Kenelm Digby.[2] He says: "By the help of plain salt petre, diluted in water, and mingled with some other fit earthly substance, that may familiarize it a little with the corn into which I endeavored to introduce it, I have made the barrenest ground far outgo the richest in giving a prodigiously plentiful harvest." His dissertation does not, however, show any true conception of the reason for the increase in the crop through the use of this fertilizer. In fact, the want of any real knowledge at that time of the composition of the plant would have made this impossible.

In 1804, Theodore de Saussure[3] published his chemical

[1] Tull, Jethro. Horse-Hoeing Husbandry. London. 1829.

[2] Digby, Kenelm. A Discourse Concerning the Vegetation of Plants. London. 1669.

[3] Saussure, Theodore de. Recherches Chimiques sur la Vegetation. Paris. 1804.

researches on plants, in which he, for the first time, called attention to the significance of the ash ingredients of plants, and pointed out that without them plant life is impossible and, further, that only the ash of the plant tissue is derived from the soil.

Justus von Liebig[1] in his writings published about the middle of the nineteenth century, emphasized still more strongly the importance of mineral matter in the plant and the extraction of this matter from the soil. He refuted the theory, at that time popular, that plants absorb their carbon from humus, but he made the mistake of attaching little importance to the presence of humus in the soil. He showed the importance of potassium and phosphorus in manures, but in his later expressions he failed to appreciate the value of nitrogenous manures, holding that a sufficient amount is washed from the atmosphere in the form of ammonia.

A true conception of the necessity for a supply of combined nitrogen in the soil was even at that time entertained by Boussingault and by Sir John Lawes, although the elaborate experiments conducted by Lawes, Gilbert, and Pugh[2] in 1857 were required to fully demonstrate the fact. Their care in conducting the experiments resulted in their sterilizing the soil with which they experimented, and hence their failure to discover the utilization of free atmospheric nitrogen by legumes.

[1] Liebig, J. Justus von. Principles of Agricultural Chemistry with Special Reference to the Late Researches Made in England. London. 1855. Also, Chemistry in its Applications to Agriculture and Physiology. New York. 1856.

[2] Lawes, J. B., Gilbert, J. H., and Pugh, E. On the Sources of the Nitrogen of Vegetation, with Special Reference to the Question whether Plants Assimilate Free or Uncombined Nitrogen. Rothamsted Memoirs, Vol. 1, No. 1. 1862.

Between 1840 and 1850, Sir John Lawes began the manufacture of bone superphosphate, and about the same time Peruvian guano and nitrate of soda were introduced into Europe. The commercial fertilizer industry thus dates from that time.

412. Classes of manures. — While manures are very numerous as to kind and while a certain manure may have a number of distinct functions, they may yet be roughly divided into classes. They will accordingly be treated here under the following heads: (1) commercial fertilizers; (2) soil amendments; (3) farm manures; (4) green manures.

413. Commercial fertilizers. — Although the commercial fertilizer industry is little more than half a century old, the sale of fertilizers in this country amounts to more than $110,000,000 annually. Animal refuse and phosphate fertilizers are exported, while nitrate of soda and potassium salts are imported.

Of the fertilizers sold in the United States in 1909, about fifty per cent was consumed in the South Atlantic States, in an area lying within three hundred miles of the seaboard. Nearly one-half of the remainder was purchased in the Middle Atlantic and New England States. Only five per cent was purchased west of the Mississippi River.[1]

Primarily the function of commercial fertilizers is to add plant nutrients to the soil, usually in a form more readily soluble than those already present in large quantity. While other beneficial effects may be produced by certain fertilizers, these are usually of secondary importance as compared with the addition of the plant nutrients.

[1] Statistics from Thirteenth Census of the United States. Abstract of the Census, p. 372. Washington. 1913.

414. **Fertilizer constituents.** — Prepared fertilizers, as found on the market, are usually composed of a number of ingredients. Since these are the carriers of the fertilizing material, and since it is on their composition and solubility that the value of a fertilizer depends, a knowledge of the properties of these constituents is of interest to every one who uses fertilizers and is a valuable aid in their purchase.

FERTILIZERS USED FOR THEIR NITROGEN

Nitrogen is the most expensive constituent of manures and is of great importance, since it is very likely to be deficient in soils. A commercial fertilizer may have its nitrogen in the form of soluble inorganic salt, or combined as organic material. On the form of combination depends to a certain extent the value of the nitrogen, as the soluble inorganic salts are very readily available to the plant, while the organic forms must pass through the various processes leading to nitrification before the plant can use the nitrogen so contained. The inorganic nitrogen fertilizers are sodium nitrate, ammonium sulfate, calcium nitrate, and calcium cyanamide.

415. **Forms in which nitrogen exists in soils.** — There are several forms in which nitrogen exists in soils. The uncombined nitrogen of the soil air constitutes the largest supply because of its diffusibility with the atmospheric air. Next in quantity is the nitrogen of organic compounds, ranging from 0.05 to 0.3 per cent in ordinary arable land and slightly, but appreciably, soluble in soil water. In upland cultivated soils the nitrogen of nitrate salts forms the next largest supply, but rarely exceeds 20 per cent of the total combined nitrogen of the soil.

In swamp and inundated soils the nitrogen of ammonium salts and nitrites forms a larger proportion of the soil nitrogen than does the nitrate nitrogen, but in well aërated soils these compounds exist in very small quantities.

416. **Forms in which nitrogen is absorbed by plants.** — The utilization of atmospheric nitrogen by leguminous plants and by a few others that have nodule-bearing roots has been established beyond question; but the extent to which this form of nitrogen may be utilized by other plants, or the identity of the plants that participate in its use, are subjects on which opinions differ, and which are still being investigated.

417. **Use of nitrates by plants.** — Boussingault first demonstrated the importance of nitrates for higher plants. Previous to that time ammonia had been considered the chief source of nitrogen, and at a still earlier time humus had been considered the source. Liebig gave the weight of his influence in favor of ammonia as the supply. He was unaware, of course, of the transformation of ammonia nitrogen into nitrates in the soil. Since the publication of the experiments by Boussingault and the later work on nitrification, there has been a tendency to consider nitrate nitrogen as the only available supply of nitrogen for agricultural plants. While this is an extreme view of the matter, the fact remains that all the higher plants, including the legumes, appear to be able to absorb nitrates, and this form of nitrogen has frequently proved of greater benefit to plants than other forms of nitrogen tested at the same time.

418. **Ammonia as a plant-food.** — That rice plants of swamps use ammonia nitrogen rather than other forms

has been demonstrated by Kellner[1] and later by Kelley.[2] On upland soils, however, it is presumable that rice plants utilize nitrate nitrogen, which would indicate that some plants, at least, may adapt themselves to the use of the more abundant form of nitrogen.

Hutchinson and Miller[3] found that peas obtained nitrogen from ammonium salts as readily as from sodium nitrate, but that wheat plants, although able to obtain nitrogen directly from ammonium salts, grew much better in a solution containing nitrates. One feature brought out by the numerous experiments with ammonium salts is the difference between plants of various kinds in respect to their ability to absorb nitrogen in this form.

419. Utilization of humus compounds by plants. One of the early beliefs in regard to plant nutrition was that organic matter as such is directly absorbed by higher plants. This opinion was afterwards entirely replaced by the mineral theory propounded by Liebig, and still later the discovery of the nitrifying process almost disposed completely of the belief that organic matter is a food for higher plants. It is quite certain, however, that some organic nitrogenous compounds furnish suitable nutrient material for some higher plants without undergoing bacterial change.

Hutchinson and Miller, in the paper just referred to, give the following list of the organic substances used in

[1] Kellner, O. Agrikulturchemische Studien über die Reiskultur. Landw. Vers. Stat., Band 30, Seite 18–41. 1884.

[2] Kelley, W. P. The Assimilation of Nitrogen by Rice. Hawaii Agr. Exp. Sta., Bul. 24, pp. 3–20. 1911.

[3] Hutchinson, H. B., and Miller, N. H. J. The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants. Centrlb. f. Bakt., II, Band 30, Seite 513–547. 1911.

experiments by various investigators, and their availability for the nutriment of higher plants:—

READILY ASSIMILATED

Ammonium salts

Acetamide $CH_3 . CO . NH_2$

Urea $CO\left\langle\begin{matrix}NH_2\\NH_2\end{matrix}\right.$

Barbituric acid (with calcium carbonate)

$$CO\left\langle\begin{matrix}NH . CO\\NH . CO\end{matrix}\right\rangle CH_2$$

Alloxan $CO\left\langle\begin{matrix}NH . CO\\NH . CO\end{matrix}\right\rangle CO$

Humates

ASSIMILATED

Formamide $H . CO . NH_2$

Glycine $NH_2 . CH_2 . COOH$

Aminopropionic acid $CH_3 . CH(NH_2) . COOH$

Guanidine hydrochloride $\left[C\begin{matrix}/NH_2\\-NH\\\backslash NH_2\end{matrix}\right]HCl$

Cyanuric acid $CO\left\langle\begin{matrix}NH . CO\\NH . CO\end{matrix}\right\rangle NH$

Oxamide $\begin{array}{l}CO . NH_2\\|\\CO . NH_2\end{array}$

Sodium aspartate $\begin{array}{l}CH(NH_2)COOH\\|\\CH_2 . COOH\end{array}$

Peptone

Doubtful

Trimethylamine

para-Urazine $CO\left\langle\begin{matrix}NH \cdot NH\\NH \cdot NH\end{matrix}\right\rangle CO$

Hexamethylenetetramine

Not Assimilated

Ethyl nitrate	Hydroxylamine hydrochloride
Propionitrile	Methyl carbonate

Toxic

Tetranitromethane

This list comprises only those substances that have been used in experiments with peas. Many other substances remain to be tested, and those already tested may act differently with other plants.

One of the organic compounds isolated from soils by Shorey,[1] called creatinine, has been shown by Skinner[2] to be used directly by plants as a source of nitrogen, and to have produced a better growth of wheat seedlings than did an equivalent quantity of nitrogen in the form of sodium nitrate. Histidine, arginine, and creatine have also been found in soils and shown to be a direct source of nitrogen for wheat seedlings (par. 92).

These and numerous other investigations of this subject show that amino as well as amide nitrogen is assimilated by at least some agricultural plants, but to what extent most of these compounds may successfully replace the

[1] Shorey, E. C. I. The Isolation of Creatinine from Soils. U. S. D. A., Bur. Soils, Bul. 83, pp. 11-33. 1911.

[2] Skinner, J. J. III. Effects of Creatinine on Plant Growth. U. S. D. A., Bur. Soils, Bul. 83, pp. 33-44. 1911.

inorganic forms of nitrogen has not been definitely worked out. Certain organic nitrogenous fertilizers — as, for example, dried blood — have a high commercial value, the nitrogen in this form selling for more a pound than the nitrogen in any of the inorganic salts. Many crops, especially among garden vegetables, are most successfully grown only when supplied with organic nitrogenous material. Some nitrate nitrogen is always present under natural soil conditions, so that crops are never limited to organic nitrogen alone; and it may be that the latter form of nitrogen is most useful when it supplements the nitrate nitrogen.

420. Sodium nitrate. — This now constitutes the principal source of inorganic nitrogen in commercial fertilizers. The salt exists in the crude condition in northern Chili. The crude salt is purified by crystallization, and as put on the market it contains about 96 per cent sodium nitrate, or about 16 per cent of nitrogen, 2 per cent of water, and small amounts of chlorides, sulfates, and insoluble matter. The cost of nitrogen in this form is from fifteen to eighteen cents a pound.

Because of its easy availability, sodium nitrate acts quickly in inducing growth. For this reason it is used much by market gardeners, and for other purposes when a rapid growth is desired. It is the most active form of nitrogen. A light dressing on meadowland in early spring assists greatly in hastening growth by furnishing available nitrogen before the conditions are favorable for the process of nitrification. On small grain a similarly useful purpose is served where the soil is not rich.

Owing to the fact that nitrate is not absorbed by the soil in large quantities, it is easily lost in the drainage water; for this reason it should be applied only when crops are growing on the soil, and then only in moderate quantity.

The continued and abundant use of sodium nitrate on the soil may result, through its deflocculating action, in breaking down aggregates of soil particles, thus compacting and injuring the structure. This effect is attributed to the accumulation of sodium salts, particularly the carbonate, as the sodium is not utilized by the plant to the same extent as is the nitrogen.

421. Ammonium sulfate. — When coal is distilled, a portion of the nitrogen is liberated as ammonia and is collected by passing the products of distillation through water in which the ammonia is soluble, forming the ammoniacal liquor. The ammonia thus held is distilled into sulfuric acid, with the formation of ammonium sulfate and the removal of impure gases.

Commercial ammonium sulfate contains about twenty per cent of nitrogen. It is the most concentrated form in which nitrogen can be purchased as a fertilizer, having from sixty to eighty pounds more of nitrogen to a ton than sodium nitrate. It is therefore economical to handle. Its effect on crops is not so rapid as that of sodium nitrate, but it is not so quickly carried from the soil by drainage water, as the ammonium salts are readily absorbed by the soil. A pound of nitrogen in the form of ammonium sulfate has about the same agricultural value as the same amount in the form of nitrate if the soil on which it is used is abundantly supplied with lime; but on an acid soil ammonium sulfate has less value.

The long and extensive use of ammonium sulfate on a soil has a tendency to produce an acid condition, through the accumulation of sulfates which are not largely taken up by plants.

Ammonium sulfate, like sodium nitrate, should not be applied in autumn, as the ammonia is converted into

nitrates and leached from the soil in sufficient quantities to entail a very decided loss of nitrogen. There is not likely to be so large a loss of nitrogen from ammonium salts as from nitrates, and, as would naturally be expected, there is greater loss of nitrogen when these salts are used alone than when they are combined with other fertilizing ingredients.

Hall[1] has estimated the loss of nitrogen from certain drained plats at the Rothamsted Experiment Station. This estimate is based on the concentration of the drainage from the different plats, of which there was no record of total flow, but for which the measurements of flow from the lysimeter draining 60 inches of soil were taken and the total loss of nitrates was calculated on this basis. Estimated in this way the effects of several different methods of manuring are shown in the accompanying table: —

POUNDS TO THE ACRE OF NITRIC NITROGEN IN DRAINAGE WATER

Treatment	1879-80		1880-81	
	Spring sowing to harvest	Harvest to spring sowing	Spring sowing to harvest	Harvest to spring sowing
Unmanured	1.7	10.8	0.0	17.1
Mineral fertilizers only	1.8	13.3	0.7	17.7
Minerals + 400 pounds ammonium salts	18.3	12.6	4.3	21.4
Minerals + 550 pounds nitrate of soda	45.0	15.6	15.0	41.0
Minerals + 400 pounds ammonium salts applied in autumn	9.6	59.8	3.4	71.9
400 pounds ammonium salts alone	32.9	14.3	7.4	34.2
400 pounds ammonium salts + sulphate of potash	19.0	16.4	3.7	25.4
Estimated drainage in inches	11.1	4.7	3.8	12.8

[1] Hall, A. D. The Book of the Rothamsted Experiments, p. 235. New York, 1905.

This table, in addition to confirming the statements already made in regard to the loss of nitrogen in drainage water, also shows how closely the supply of available nitrogen was used by the crops on those plats, which were evidently in need of nitrogen fertilization as the plats lost very little nitrogen during the growing season, while during the remainder of the year they lost nearly as much as did some of the nitrogen-manured plats. The table also indicates that the loss when nitrate is used is greater than when ammonium salts are applied, as the amount of nitrogen in the 650 pounds of nitrate is really eight pounds to the acre more than in the 400 pounds of ammonium sulfate, which is not sufficient to account for the difference in the loss. However, half of the nitrate-treated plat received no other manure and produced only a small crop, which would naturally result in a greater loss by drainage.

422. Fertilizers containing atmospheric nitrogen. — The vast store of atmospheric nitrogen, chemically uncombined but very inert, will furnish an inexhaustible supply of this highly valuable fertilizing element, when it can with reasonable economy be combined in some manner resulting in a product that will be commercially transportable and that will, when placed in the soil, be or become soluble without liberating substances toxic to plants. The importance of the nitrogen supply for agriculture may be appreciated when it is considered that nitrates are being carried off in the drainage water of all cultivated soils at the rate of twenty-five to fifty pounds, and even more, to the acre annually, and that nearly as much more is removed in crops.

The exhaustion of the supply of nitrogen in most soils may be accomplished within one or two generations of

gen, unless a renewal of the supply is brought about in some way. Natural processes provide for an annual accretion through the washing-down of ammonia and nitrates by rain water from the atmosphere, and through the fixation of free atmospheric nitrogen by bacteria; but without the frequent use of leguminous crops, the supply could not be maintained. Farm practice of the present day requires the application of nitrogen in some form of manure, and, as the end of the commercial supply of combined nitrogen is easily in sight, there is urgent need of discovering a new source. This has been done by combining calcium with atmospheric nitrogen in the forms of calcium cyanamide and calcium nitrate.

423. **Cyanamid.** — The trade name for calcium cyanamide is "cyanamid" and that name is therefore used in this volume. One process for the production of cyanamid consists in passing nitrogen into closed retorts containing powdered calcium carbide heated to a high temperature; the product being calcium cyanamide and free carbon: —

$$CaC_2 + 2N = CaCN_2 + C$$

The free carbon remains distributed in the cyanamide and gives the fertilizer a black color. The nitrogen required for the process is obtained either by passing air over heated copper, or by the fractional distillation of liquid air.

The fertilizer, as placed on the market, is a heavy, black powder or granulated material with a somewhat disagreeable odor.

424. **Composition of cyanamid.**[1] — Cyanamid as man-

[1] Cyanamid is a trade name; the chemical compound is spelled cyanamide.

factured in this country has about the following composition:[1] —

		Per cent
Calcium cyanamide	$CaCN_2$	45.92
Calcium carbonate	$CaCO_3$	4.04
Calcium sulfide	CaS	1.73
Calcium phosphide	Ca_3P_2	0.04
Calcium hydroxide	$Ca(OH)_2$	26.60
Free carbon	C	13.14
Iron and alumina	R_2O_3	1.98
Silica	SiO_2	1.62
Magnesia	MgO	0.15
Combined moisture		3.12
Free moisture	H_2O	0.35
Undetermined		1.31
		100.00

According to this composition the material would contain 16 per cent of nitrogen. Lime in the forms of carbonate and hydroxide would add somewhat to its value, and the residue of the calcium cyanamide, which upon decomposition is also calcium hydroxide, is likewise beneficial to the soil.

435. Changes of calcium cyanamide in the soil. — Calcium cyanamide must be decomposed in the soil before its nitrogen becomes available to plants. There are several steps in the decomposition process by which the nitrogen finally emerges in the form of ammonia. These, according to Pranke in the work just cited, consist first of hydrolysis, by which acid calcium cyanamide and calcium hydroxide are formed: —

$$\underbrace{2\,CN.NCa}_{\text{calcium cyanamide}} + \underbrace{2\,H_2O}_{\text{water}} = \underbrace{(CN.NH)_2Ca}_{\text{acid calcium cyanamide}} + \underbrace{Ca(OH)_2}_{\text{calcium hydroxide}}$$

[1] Pranke, E. J. Cyanamid, p. 8. Easton, Pennsylvania. 1913.

The acid calcium cyanamide quickly loses its calcium, leaving free cyanamide. Investigators differ as to the process involved in this change, but the ultimate condition of the calcium is carbonate. The three explanations of the process may be represented by the following reactions:—

$$1.\ (CN.NH)_2Ca + CO_2 + H_2O = 2\,CN.NH_2 + CaCO_3$$

In this reaction the carbon dioxide of the soil water is supposed to cause precipitation of the calcium.

$$2.\ (CN.NH)_2Ca + 2\,H_2O = 2\,CN.NH_2 + Ca(OH)_2$$

In this case hydrolysis occasions the reaction. The hydroxide would, of course, be converted into carbonate in the soil.

$$3.\ \underset{\text{acid calcium cyanamide}}{(CN.NH)_2Ca} + \underset{\text{carbon dioxide}}{CO_2} = \underset{\text{free cyanamide}}{CN.NH_2} + \underset{\text{calcium cyanamide carbonate}}{CaCN_2CO_2}$$

$$CaCN_2CO_2 + H_2O = \underset{\text{free cyanamide}}{CN.NH_2} + \underset{\text{calcium carbonate}}{CaCO_3}$$

By this reaction calcium cyanamide carbonate is an intermediate product, but is at once hydrolyzed and free cyanamide produced.

The next step in the process is the formation of urea by hydrolysis of the free cyanamide:—

$$\underset{\text{free cyanamide}}{CN.NH_2} + \underset{\text{water}}{H_2O} = \underset{\text{urea}}{CO(NH_2)_2}$$

The changes up to the production of urea are independent of bacterial action. The urea is converted through bacterial action into ammonium carbonate:—

$$\underset{\text{urea}}{CO(NH_2)_2} + 2\,H_2O = \underset{\text{ammonium carbonate}}{(NH_4)_2CO_3}$$

This may be converted into nitrates in the usual manner.

436. **The use of cyanamid.** — The changes as here described are those that prevail under favorable conditions in the soil. When conditions are not favorable — as, for example, when a soil is saturated with water or when it is acid — some more or less injurious products may be formed. For this reason cyanamid is not likely to be so satisfactory on soils of this nature as on better soils. To very sandy soils it is not well suited. Ordinarily its fertilizing value is not greatly below that of sodium nitrate, and is about equal to that of ammonium sulfate when not used in heavy applications.

It should be incorporated with the soil at least a week before planting, as it may injure the young plants if decomposition has not proceeded far enough to remove its somewhat toxic properties. As it must undergo this decomposition before its nitrogen becomes available to the young plants, there is an added reason for this precaution. It does not give its best results as a top-dressing because it requires incorporation with the soil for its proper decomposition.

437. **Calcium nitrate.** — The other process for combining atmospheric nitrogen is of more recent invention than that for the manufacture of calcium cyanamid but is not conducted on a commercial scale in this country; however, with the vast opportunities for developing electric power which are offered in certain localities, factories for the manufacture of calcium nitrate will some day be established.

The process employs an electric arc to produce nitric

oxide by the combustion of atmospheric nitrogen, according to the simple equation:

$$N_2 + O_2 = 2\,NO$$
$$NO + O = NO_2$$

A very high power is required for this synthesis, involving a temperature of 2500° to 3000° C., and the expense of the operation is determined almost entirely by the cost of the electricity.

The nitric oxide gas is passed through milk of lime, giving basic calcium nitrate: —

$$Ca(OH)_2 + 2\,HNO_3 = Ca(NO_3)_2 + 2\,H_2O$$

The calcium nitrate resulting from this process has a yellowish white color, and is easily soluble in water but deliquesces very rapidly in the air. This last property can be overcome by adding an excess of lime in the manufacture, thus producing a basic calcium nitrate which contains only 8.9 per cent of nitrogen. Another way of avoiding the difficulties involved by the deliquescent property of the nitrate is practiced by the factory at Notodden, Norway. This consists in first melting the product, then grinding it fine and packing it in air-tight casks. The fertilizer thus prepared contains from 11 to 13 per cent of nitrogen.

Calcium nitrate contains its nitrogen in a form directly available to plants. It resembles sodium nitrate in its solubility, availability, and lack of absorption by the soil. It may be spread on the surface of the ground, as it exerts no poisonous action and does not tend to form a crust, as does sodium nitrate.

The relative values of the different soluble nitrogen fertilizers vary with a great many conditions and can be

accurately judged only by a large number of tests. At present, both calcium nitrate and cyanamid are being produced at less cost per pound of nitrogen than is sodium nitrate, when laid down in the neighborhood of the factories in Europe. It seems fairly certain that, when the processes have been further improved, the result will be to greatly reduce the cost of available nitrogen.

423. **Organic nitrogen in fertilizers.** — The commercial fertilizers containing organic nitrogen include cottonseed meal, which contains 7 per cent of nitrogen when free from hulls; linseed meal, with 5.5 per cent of nitrogen; castor pomace, with 6 per cent of nitrogen; and a number of refuse products from packing houses, among which are red dried blood and black dried blood, the former having about 13 per cent of nitrogen and the latter from 6 to 12 per cent; dried meat and hoof meal, with 12 to 13 per cent of nitrogen; ground fish, with 8 per cent of nitrogen; and tankage, of which the concentrated product has a nitrogen content of from 10 to 12 per cent and the crushed tankage from 4 to 9 per cent; also leather meal and wool-and-hair waste, but these, because of their mechanical condition, are of very little value.

The meals made from seeds are primarily stock foods but are sometimes used as manures. They decompose rather slowly in the soil, owing to their high oil content, and are much more profitably fed to live stock than applied as farm manure. They contain some phosphorus and potash as well as nitrogen.

Guano consists of the excrement and carcasses of sea fowl. The composition of guano depends on the climate of the region in which it is found. Guano from an arid region contains nitrogen, phosphorus, and potassium, while that from a region where rains occur contains only phos-

phorus — the nitrogen and potassium having been largely leached out. In a dry guano the nitrogen exists as uric acid, urates and, in small quantities, ammonium salts. A damp guano contains more ammonia. The phosphorus is present as calcium phosphate, ammonium phosphate, and the phosphates of other alkalies. A portion of the phosphate is readily soluble in water. Thus all the plant-food either is directly soluble or becomes so soon after admixture with the soil. The composition is extremely variable. The best Peruvian guano contains from 10 to 12 per cent of nitrogen, from 12 to 15 per cent of phosphoric acid, and from 3 to 4 per cent of potash.

Guano was formerly a very important fertilizing material, but the supply has become so nearly exhausted that it is relatively unimportant at the present time.

Of the abattoir products, dried blood is the most readily decomposed, and therefore has its nitrogen in the most available form. In fact, it produces results more quickly than any other form of organic nitrogen. It requires a condition of soil favorable to decomposition and nitrification, which prevents its exerting a strong action in early spring. It should be applied to the soil before the crop is planted. The black dried blood contains from 2 to 4 per cent of phosphoric acid.

Dried meat contains a high percentage of nitrogen, but does not decompose so easily as dried blood, and is not so desirable a form of nitrogen. It can be fed to hogs or poultry to advantage, and the resulting manure is very high in nitrogen.

Hoof meal, while high in nitrogen, decomposes slowly, being less active than dried blood. It is of use in increasing the store of nitrogen in a depleted soil.

Ground fish is an excellent form of nitrogen, and is as readily available as blood but has a lower nitrogen content.

Tankage is highly variable in composition, and the concentrated tankage, being more finely ground, undergoes more readily the decomposition necessary for the utilization of the nitrogen. Crushed tankage contains from 3 to 12 per cent of phosphoric acid, in addition to its nitrogen.

Leather meal and wool-and-hair waste when untreated are in such a tough and undecomposable condition that they may remain in the soil for years without losing their structure. They are not to be recommended as manures.

429. Availability of organic nitrogenous fertilizers. — The forms in which combined nitrogen is available to most agricultural plants has already been stated to be nitrates, ammonium salts, and certain organic compounds. Of the latter the simple compounds, as urea, appear to be most readily taken up by plants. Decomposition is therefore a necessary process for most of these fertilizers, and their usefulness is, in general, proportional to the readiness with which aërobic decomposition proceeds, or to the proportion of available compounds that they contain in their original condition. Guano, for instance apparently, contains much nitrogen that is available without further decomposition. Dried blood quickly decomposes and soon forms available substances, consisting of the simpler organic nitrogenous compounds, ammonia and nitrates. The decomposition process is a biological one, arising from the action of microörganisms that first break down the complicated organic compounds, forming simpler ones, and finally carry the nitrogen into the form of ammonia, then to nitrous acid, and at last to nitric acid.

Numerous attempts have been made to determine the relative availability of the nitrogen in various organic

nitrogenous fertilizers. A few such tests, in which nitrate of soda and ammonium sulfate are used as a basis for comparison, are given in the table below, the statement being in terms of percentage availability when nitrate of soda is taken as one hundred. The experiments quoted were conducted by Wagner and Dorsch,[1] by Johnson, Jenkins, and Britton,[2] and by Voorhees and Lipman.[3]

PERCENTAGE AVAILABILITY OF FERTILIZER NITROGEN

	WAGNER AND DORSCH	JOHNSON AND OTHERS	VOORHEES AND LIPMAN
Nitrate of soda	100	100	100
Sulfate of ammonia	90		70
Dried blood	70	73	64
Bone meal	60	17	
Stable manure	45		53
Tankage		49	
Horn and hoof meal	70	68	
Linseed meal		80	
Cottonseed meal		65	
Castor pomace		65	
Wool waste	30		
Leather meal	20		
Dry ground fish		64	

One difficulty in drawing conclusions from these experiments is that the substances grouped under the same name are not always identical in the method of their

[1] Wagner, P., and Dorsch, R. Die Stickstoffdüngung der Landw. Kulturpflanzen, Erster Teil. Berlin. 1892.

[2] Johnson, S. W., Jenkins, E. H., and Britton, W. E. Experiments on the Availability of Fertilizer-Nitrogen. Connecticut Agr. Exp. Sta., 21st Annual Rept., Part 4, pp. 257–277. 1897.

[3] Voorhees, E. B., and Lipman, J. G. Investigations Relative to the Use of Nitrogenous Materials, 1898–1907. New Jersey Agr. Exp. Sta., Bul. 221. 1909.

preparation or in their composition. Another discrepancy arises from the fact that all soils do not respond in the same relative degree to any one fertilizer. Thus, Sackett[1] found that in some soils dried blood was ammonified more rapidly than was cottonseed meal, while in other soils the reverse was true; and that a similar difference obtained in soils with respect to the ammonification of alfalfa meal and flaxseed meal. It would therefore appear to be impossible to make any close distinctions in the relative availability of the nitrogen in various organic nitrogenous fertilizers. A considerable number of these experiments are, in the aggregate, useful in pointing out the probable relative availabilities of the more widely differing nitrogen-bearing substances.

FERTILIZERS USED FOR THEIR PHOSPHORUS

Phosphorus is generally present in combination with lime, iron, or alumina. Some of the phosphates contain also organic matter, in which case they generally carry some nitrogen. Phosphates associated with organic matter decompose more quickly in the soil than do untreated mineral phosphates.

420. **Bone phosphate.** — Formerly bones were used entirely in the raw condition, ground or unground. When ground they act as a fertilizer more quickly than when unground. Raw bones contain about 23 per cent of phosphoric acid and 4 per cent of nitrogen. The phosphorus is in the form of tricalcic phosphate ($Ca_3(PO_4)_2$).

Most of the bone now on the market is first boiled or

[1] Sackett, W. G. The Ammonifying Efficiency of Certain Colorado Soils. Colorado Agr. Exp. Sta., Bul. 184, pp. 3-23. 1912.

steamed. This frees it from fat and nitrogenous matter, both of which are used in other ways. Steamed bone is more valuable as a fertilizer than raw bone, because the fat in the latter retards decomposition and also because steamed bone is in a better mechanical condition. The form of the phosphoric acid is the same as in raw bone and constitutes from 28 to 30 per cent of the product, while the nitrogen is reduced to 1½ per cent.

Bone tankage, which has already been spoken of as a nitrogenous fertilizer, contains from 7 to 9 per cent of phosphoric acid, largely in the form of tricalcium phosphate. All these bone phosphates are slow-acting manures, and should be used in a finely ground form and for the permanent benefit of the soil rather than as an immediate source of nitrogen or phosphorus.

431. Mineral phosphates. — There are many natural deposits of mineral phosphates in different parts of the world, some of the most important of which are in North America. The phosphorus in all these is in the form of tricalcium phosphate, but the materials associated with it vary greatly.

Apatite is found in large quantities in the provinces of Ontario and Quebec, Canada. It exists chiefly in crystalline form. The tricalcium phosphate of which it is composed is in one form associated with calcium fluoride and in the other with calcium chloride. The Canadian apatite contains about 40 per cent of phosphoric acid, being richer than that found elsewhere. Phosphorite is another name for apatite, but is chiefly applied to the impure amorphous form.

Coprolites are concretionary nodules found in the chalk or other deposits in the south of England and in France. They contain from 25 to 30 per cent of phos-

phoric acid, the other constituents being calcium carbonate and silica.

South Carolina phosphate contains from 26 to 28 per cent of phosphoric acid and a very small amount of iron and alumina. As these substances interfere with the manufacture of superphosphate from rock, their presence is very undesirable — rock containing more than from 3 to 6 per cent being unsuitable for that purpose.

Florida phosphates exist in the form of soft phosphate, pebble phosphate, and bowlder phosphate. Soft phosphate contains from 18 to 30 per cent of phosphoric acid, and because of its being more easily ground than most of these rocks it is often applied to the land without being first converted into a superphosphate. The other two forms, pebble phosphate and bowlder phosphate, are highly variable in composition, ranging from 20 to 40 per cent in phosphoric acid content. Tennessee phosphate contains from 30 to 35 per cent of phosphoric acid.

Basic slag, or, as it is also called, phosphate slag or Thomas phosphate, is a by-product in the manufacture of steel from pig-iron rich in phosphorus. The phosphorus present is usually considered to be in the form of tetracalcium phosphate, $(CaO)_4P_2O_5$, or possibly a double silicate and phosphate of lime having the composition $(CaO)_5P_2O_5SiO_2$. It contains also calcium, magnesium, aluminium, iron, manganese silica, and sulfur. Because of the presence of iron and aluminium, and because its phosphorus is more readily soluble than tricalcium phosphate, the ground slag is applied directly to the soil without treatment with acid.

The degree of fineness to which the slag is ground is supposed to be an important factor in determining its solubility in the soil. It is much more soluble in water

charged with carbon dioxide than in pure water, a property that greatly increases its value because of the fact that soil water always contains more or less of this gas. It is also readily acted upon by organic acids. For this reason it is particularly effective in a peat soil, and likewise in most soils deficient in lime. As it contains a considerable quantity of free lime it has another beneficial effect on such soils.

432. Superphosphate fertilizers. — In order to render more readily available to plants the phosphorus contained in bone and mineral phosphates, the raw material, purified by being washed and finely ground, is treated with sulfuric acid. This results in a replacement of phosphoric acid by sulfuric acid, with the formation of monocalcium phosphate and calcium sulfate, and a smaller amount of dicalcium phosphate, according to the reactions: —

$$Ca_3(PO_4)_2 + 2\,H_2SO_4 = CaH_4(PO_4)_2 + 2\,CaSO_4$$
$$Ca_3(PO_4)_2 + H_2SO_4 = Ca_2H_2(PO_4)_2 + CaSO_4$$

The tricalcium phosphate being in excess of the sulfuric acid used, some of it remains unchanged.

In the treatment of phosphate rock some of the sulfuric acid is consumed in acting on the impurities present, which usually consist of calcium and magnesium carbonates, iron and aluminium phosphates, and calcium chloride or fluoride, converting the bases into sulfates and freeing carbon dioxide, water, hydrochloric acid, and hydrofluoric acid. The resulting superphosphate is therefore a mixture of monocalcium phosphate, dicalcium phosphate, tricalcium phosphate, calcium sulfate, and iron and aluminium sulfates.

In the superphosphates made from bone, the iron and aluminium sulfates do not exist in any considerable

quantities. However, as long as the phosphorus remains in the form of monocalcium phosphate, the value of a pound of available phosphorus in the two kinds of fertilizer is the same; but the remaining tricalcium phosphate has a greater value in the bone than in the rock superphosphate.

The superphosphates made from animal bone contain about 12 per cent of available phosphoric acid and from 3 to 4 per cent of insoluble phosphoric acid. They also contain some nitrogen. Bone ash and bone black superphosphates contain practically all their phosphorus in an available form, but they contain little or no nitrogen. South Carolina rock superphosphate contains from 12 to 14 per cent of available phosphoric acid, including from 1 to 3 per cent of reverted phosphoric acid. The best Florida rock superphosphates contain from 17 per cent downward of available phosphoric acid, some of which is reverted. The Tennessee superphosphates contain from 14 to 18 per cent of available phosphoric acid.

Double superphosphates. — In making superphosphates a material rich in phosphorus must be used, not less than 60 per cent of tricalcium phosphate being necessary for their profitable production. The poorer materials are sometimes used in making what is known as double superphosphates. For this purpose they are treated with an excess of dilute sulfuric acid; the dissolved phosphorus and the excess of sulfuric acid are separated from the mass by filtering, and are then used for treating phosphates rich in tricalcium phosphate and thus forming superphosphates. The superphosphates so formed contain more than twice as much phosphorus as those made in the ordinary way.

488. **Reverted phosphoric acid.** — A change sometimes occurs in superphosphates on standing by which some of

the phosphoric acid becomes less easily soluble, and to that extent the value of the fertilizer is decreased. This change, known as reversion, is much more likely to occur in superphosphates made from rock than in those derived from bone. It will also vary in different samples, a well-made article usually undergoing little change even after long standing. It is supposed to be caused by the presence of undecomposed tricalcium phosphate and of iron and aluminium sulfates.

434. Relative availability of phosphate fertilizers. — Superphosphates and double superphosphates contain their phosphorus in a form in which it can be taken up by the plant at once. They are therefore best applied at the time when the crop is planted, or shortly before, or they may be applied when the crop is growing. Crude phosphates, on the other hand, become available only through the natural processes in the soil. They should be applied in quantity sufficient to meet the needs of the crops for a number of years.

Reverted phosphorus, although not soluble in water, is readily soluble in dilute acids. It is now generally believed that in this form an available supply of phosphorus is furnished to the plant. In a statement of fertilizer analyses reverted phosphorus is termed *citrate-soluble*, and this and the *water-soluble* are termed *available*.

The degree of fineness to which the material is ground makes a great difference in the availability of the less soluble phosphate fertilizers, especially in the ground-rock phosphates and in ground bone. This material should be ground fine enough to pass through a sieve having meshes at least one-fiftieth of an inch in diameter.

435. Changes that occur when superphosphate is added to soils. — When incorporated with soils superphosphate

undergoes changes, the nature of which depends more or less on the properties of the particular soil with which it is mixed. No matter how readily soluble the phosphorus may be in the fertilizer, it soon becomes insoluble in the soil, only a fractional proportion of it being recoverable in water extracts. Absorption by colloidal complexes is the fate of a part of the phosphorus, in which condition it is still available to plants, especially when the colloidal matter becomes coagulated. The excess phosphorus enters into combination with the calcium of the soil, forming tricalcium phosphate and some dicalcium phosphate, and with the iron or the aluminium, forming phosphates of these metals. The latter compounds are less readily soluble than the former, and probably do not serve as a direct source of phosphorus for plants; while tricalcium phosphate, although acted upon by plant roots, is not so readily available as is the phosphorus held by the colloidal matter.

It is desirable that there should be an abundant supply of calcium in a soil to which a superphosphate is added, because the phosphorus not absorbed by the colloidal matter of the soil will, under such circumstances, form more calcium phosphate than if only a small supply of lime is present, according to the law of mass action. The great loss of availability through the conversion of phosphorus into iron and aluminium phosphates may thus be mitigated.

436. Other factors influencing the availability of tricalcium phosphate. — As this is the form in which phosphorus is probably most extensively held in the ordinary soil, and as it is also a cheap form of phosphorus in manures, it is a matter of some importance to know the most favorable conditions for its utilization by agricultural plants. Experimentation by numerous investigators has established at least four factors that influence the availability

of this substance: (1) kind of plant grown; (2) degree of basicity of soil; (3) fermentation of organic matter; (4) character of the accompanying salts.

437. Effect of plants on the availability of tricalcium phosphate. — It is to be expected that the various kinds of plants should not all exert an equal influence on the availability of the phosphorus of tricalcium phosphate. Prianischnikov[1] found that lupines, mustard, peas, buckwheat, and vetch responded to fertilization with raw rock phosphate in the order named, while the cereals did not respond at all. He did not include maize in his experiments, but that crop is said to respond well to difficultly soluble phosphates. It is generally considered that those plants which have a long growing season are better able to utilize tricalcium phosphate than are more rapidly growing plants. An explanation for the ability of some plants to utilize the phosphorus of difficultly soluble phosphates more successfully than do other plants has been sought in the rate of excretion of carbon dioxide by plant roots. It has already been stated (par. 324) that Stoklasa and Ernest found[2] that the capacity of a plant to absorb phosphorus from difficultly soluble phosphates is proportional to the rate at which carbon dioxide is given off by the roots, but that the experiments of Kossowitch and Barakoff failed to confirm these results. This question is bound up with the larger one involving the solvent action of plant roots, regarding which little is now known.

438. Effect of basicity on the availability of tricalcium phosphate. — It is recognized that raw rock phosphate is more available to the same plant in some soils than in others, and a number of persons have stated, as the result

[1] Prianischnikov, D. Bericht über Verschiedene Versuche mit Rohphosphaten unter Redaction. Moscow. 1910.

of experimentation, that the availability is greater in acid soils than in those strongly basic. If acidity of the soil is due to the presence of free acid (positive acidity), it is conceivable that the availability may be due to the solvent action of the soil acid on the calcium of the tricalcium phosphate, producing the dicalcium salt which appears to be fairly readily available to plants. When, however, soil acidity is due to a lack of basicity (apparent acidity), the case is different. Gedroiz[1] explains this on the basis of the absorptive properties of the apparently acid soil. He regards rock phosphate, not as a chemical compound, but as a solid solution of dicalcium phosphate with lime. It is this excessive basicity of the phosphate which is responsible for its unavailability. Absorption of the excess calcium would leave the phosphate in a more readily available condition by forming the dicalcium salt, and this is brought about in an apparently acid soil.

Gedroiz experimented with a highly basic soil that did not respond to fertilization with rock phosphate. He subjected this soil to repeated washings with distilled water charged with carbon dioxide. After such treatment the soil gave a marked increase in crop with rock phosphate as compared with the same soil untreated. According to Gedroiz the greater availability of the phosphate after treatment with carbonic acid was due to the removal of bases and the greater absorptive power of the soil brought about thereby. This was further corroborated by the fact that the treated soil responded to a test for unsaturation while the untreated soil did not. Without

[1] Gedroiz, K. K. Soils to which Rock Phosphates may be Applied with Advantage. Jour. Exp. Agronomy (Russian), Vol 12, pp. 529–530, 811–816. 1911. The authors are indebted to Dr. J. Davidson for the translation.

necessarily accepting all of Gedroiz's explanation of the phenomenon, there can be little doubt that lack of basicity is a factor in the availability of raw rock phosphates in some soils.

439. Influence of fermenting organic matter. — There has been great difference of opinion among investigators as to the effect of fermentation of organic matter on the availability of the phosphorus of tricalcium phosphate. The contention that the availability is increased probably originated with Stoklasa,[1] the results of whose experiments with bone meal indicated that the availability is increased by fermentation. A large number of experiments have been conducted with raw rock phosphate composted with stable manure, among which may be mentioned those by Hartwell and Pember[2] and also by Truog,[3] Tottingham and Hoffman,[3] who in carefully conducted experiments failed to find that the availability of the raw phosphate was increased by fermentation with stable manure. Opposing results have also been obtained, however, and the evidence is somewhat conflicting. Kröber,[4] who thinks that the action of bacteria is due to the acids they produce, explains the contradictions in the various

[1] Stoklasa, J., Duchacek, F., and Pitra, J. Ueber den Einfluss der Bakterien auf die Knochenzersetzung. Centbl. f. Bakt., II, Band 6, Seite 526–535, 554–558. 1900.

[2] Hartwell, B. L., and Pember, F. R. The effect of dung on the availability of rock phosphate. Rhode Island Agr. Exp. Sta., Bul. 151. 1912.

[3] Tottingham, W. E., and Hoffman, C. The Nature of the Changes in Solubility and Availability of Phosphorus in Fermenting Mixtures. Wisconsin Agr. Exp. Sta., Research Bul. 29. 1913.

[4] Kröber, E. Ueber das Löslichwerden der Phosphorsäure aus Wasserunlöslichen Verbindungen unter der Einwirkung von Bakterien und Hefen. Jour. f. Landw., Band 57, Seite 5–80. 1909–1910.

experiments as arising from the different kinds of fermentation that the organic matter undergoes. He thinks that acid fermentation renders the phosphate more readily soluble, while fermentation that does not give rise to acids leaves it in an insoluble condition.

Parallel with the biological process that results in the transformation of insoluble phosphates into soluble, there is, according to Stoklasa and others, a reverse biological process resulting in the transformation of soluble phosphates into insoluble.

Whatever may be the conditions under which raw rock phosphate is rendered more readily soluble or available by fermentation of organic matter, it does not appear that composting with stable manure produces this change, at least from results of numerous experiments including those mentioned above. These have been mainly opposed to any such conclusion.

440. **Influence of other salts.** The presence of certain salts has been found to influence the availability of difficultly soluble phosphates. The subject has been investigated by a large number of experimenters and it will be possible to summarize their results only in part and very briefly. It has been found, for instance, that calcium carbonate decreases the availability of raw rock phosphate and bone-meal. Sodium nitrate reduces the availability of the tricalcium phosphates, while the ammonium salts increase their availability. Iron salts decrease availability. The influence of other salts has not been so well worked out. Prianischnikov,[1] as the result of his extended experiments on the subject, holds that

[1] Prianischnikov, D. Ueber den Einfluss von Kohlensaurem Kalk auf die Wirkung von Verschiedenen Phosphaten. Landw. Vers. Stat., Band 75, Seite 357-376. 1911.

salts from which plants absorb acid in larger amounts than they do bases decrease availability, or at least do not affect it, while salts from which plants absorb the bases in greater quantity than the acids have a tendency to render the phosphate more available, because of the solvent action of the acid.

FERTILIZERS USED FOR THEIR POTASSIUM

The production of potassium fertilizers is largely confined to Germany, where there are extensive beds varying from 50 to 150 feet in thickness, lying under a region of country extending from the Harz Mountains to the Elbe River and known as the Stassfurt deposits. Deposits have lately been discovered in other parts of Germany.

441. Stassfurt salts. — The Stassfurt salts contain their potassium either as a chloride or as a sulfate. The chloride has the advantage of being more diffusible in the soil, but in most respects the sulfate is preferable. Potassium chloride in large applications has an injurious effect on certain crops, among which are tobacco, sugar beets, and potatoes. On cereals, legumes, and grasses, the muriate appears to have no injurious effect.

The mineral produced in largest quantities by the Stassfurt mines is kainit. Chemically it consists of magnesium and potassium sulfate and magnesium chloride, or of magnesium sulfate and potassium chloride. Kainit has the same effect on plants as has potassium chloride. It contains from 12 to 20 per cent of potash and from 25 to 45 per cent of sodium chloride, with some chloride and sulfate of magnesium.

Kainit should be applied to the soil a considerable time before the crop for which it is intended is planted.

It should not be drilled in with the seed, as the action of the chlorides in direct contact with the seed may injure its viability. In addition to the potassium added to the soil by kainit, there are also in this fertilizer magnesium and sodium. The magnesium may be objectionable if there is much already present in the soil (see par. 458). Sodium may to some extent replace potassium in the soil economy, and in that way may be beneficial.

Silvinit contains its potassium both as chloride and as sulfate. It also contains sodium and magnesium chlorides. Potash constitutes about 16 per cent of the material. Owing to the presence of chlorides, it has the same effect on plants as has kainit.

The commercial form of potassium chloride generally contains about 80 per cent of potassium chloride or 50 per cent of potash. The impurities are largely sodium chloride and insoluble mineral matter. The possible injury to certain crops from the use of the chloride has already been mentioned. For crops not so affected, potassium chloride is a quickly acting and effective carrier of potassium, and one of the cheapest forms.

High-grade sulfate of potassium contains from 48 to 50 per cent of potash. Unlike the muriate it is not injurious to crops, but is more expensive.

There are a number of other Stassfurt salts, consisting of mixtures of potassium, sodium, and magnesium in the form of chlorides and sulfates. They are not so widely used for fertilizers as are those mentioned above.

442. Wood ashes. — For some time after the use of fertilizers became an important farm practice, wood ashes constituted a large proportion of the source of supply of potassium. They also contain a considerable quantity of lime and a small amount of phosphorus. The product

known as unleached wood ashes contains from 5 to 6 per cent of potash, 2 per cent of phosphoric acid, and 30 per cent of lime. Leached wood ashes contain about 1 per cent of potash, $1\frac{1}{2}$ per cent of phosphoric acid, and from 28 to 34 per cent of lime. They contain the potassium in the form of a carbonate, which is alkaline in its reaction and in large amount may be injurious to seeds. They are beneficial to acid soils through the action of both the potassium and calcium salts. The lime is valuable for the other effects it has on the properties of the soil. (See pars. 451-457.)

443. Insoluble potassium fertilizers. — Insoluble forms of potassium, existing in many rocks usually in the form of a silicate, are not regarded as having any manurial value. Experiments with finely ground feldspar have been conducted by a number of investigators, but have, in the main, given little encouragement for the successful use of this material. An insoluble form of potassium is not given any value in the rating of a fertilizer based on the results of its analysis.

SULFUR AND SULFATES AS FERTILIZERS

The use of these substances as a means of increasing plant growth when applied to soils has recently received revived attention. The use of free sulfur has been investigated to some extent in France and Germany. There have been suggested three ways in which it may be beneficial to plants (1) as a direct stimulant; (2) by its influence on the activities of microörganisms; (3) as a source of plant-food, which might otherwise be deficient.

444. The use of free sulfur. — Boullanger[1] added flowers of sulfur to a soil at the rate of 23 parts to a million

[1] Boullanger, E. Action du soufre en fleur sur la végétation. Compt. Rend. Acad. Sci. Paris, T. 154, pp. 369-370. 1912.

of soil. He obtained increased growth in all treated soils on which carrots, beans, celery, lettuce, sorrel, chicory, potatoes, onions, and spinach were grown, the weight of the crops on the treated soil being from 10 per cent to 40 per cent greater than those on the untreated soil. On soils that had been sterilized before applying sulfur the effect was much less, from which he concludes that the beneficial effects were due to the influence of the sulfur on the microörganisms of the soil. There may be some question, however, whether this conclusion is justifiable. Sulfur was found by Boullanger and Dugardin[1] to favor ammonification in soils. Beneficial effects from the use of free sulfur have also been obtained by Demolon,[2] and by Bernhard[3] among others, while von Feilitzen[4] found it to be ineffective as a fertilizer.

That free sulfur may, under some conditions, exert a beneficial influence on plant growth must undoubtedly be conceded, but how the action is brought about remains to be conclusively demonstrated. Free sulfur is insoluble and cannot be absorbed by plant roots. However it is readily oxidized in soils[5] eventually producing sulfates with bases in the soil and in this form may readily be taken up by plants.

[1] Boullanger, E., and Dugardin, M. Mécanisme de l'action fertilisante du soufre. Compt. Rend. Acad. Sci. Paris, T. 155, pp. 327–329. 1912.

[2] Demolon, A. Sur l'action fertilisante du soufre. Compt. Rend. Acad. Sci. Paris, T. 154, pp. 524–526. 1912.

[3] Bernhard, A. Versuche über die Wirkung des Schwefels als Dung im Jahre 1911. Deutsche Landw. Presse. Band 39, p. 275. 1912.

[4] von Feilitzen, H. Ueber die Verwendung des Schwefelblüte zur Bekämpfung des Kartoffelschorfes und als indirektes Düngemittel. Fühling's Landw. Zeit. Band 62, Heft 7. 1913.

[5] Massé, M. N. Des transformations que subit le soufre en poudre quand il est répandu sur le sol. Compt. Rend. Acad. Sci. Paris, T. 09, pp. 976–979. 1889.

445. Sulfur as sulfate. — There is less experimental evidence regarding the effect of sulfur in the form of sulfate on plant growth than there is for the free sulfur. The fact that the bases with which the sulfate is combined are likely to have an effect on plant growth, makes the accumulation of proof by experimentation a somewhat more difficult matter. That there may be a possible deficiency of sulfur in arable soils has been pointed out by several investigators, including Hart and Peterson[1] in this country. They point out that crops remove more sulfur from the soil than was shown by the early determinations of sulfur in plant ash, from which a large part of the sulfur was volatilized during the process. They then proceed to calculate the sulfur removed by a number of crops on the basis of their own methods and compare this with the phosphorus in similar crops.

POUNDS SULFUR TRIOXIDE AND PHOSPHORUS PENTOXIDE REMOVED TO THE ACRE BY AVERAGE CROPS

CROP AND YIELD TO THE ACRE	CONTENT IN POUNDS TO THE ACRE	
	SO_3	P_2O_5
Wheat (30 bu.)	15.7	21.1
Barley (40 bu.)	14.3	20.7
Oats (45 bu.)	19.7	18.7
Corn (30 bu.)	12.0	18.0
Alfalfa (9000 lb. dry wt.)	64.8	39.9
Turnips (4657 lb. dry wt.)	92.2	33.1
Cabbage (4800 lb. dry wt.)	98.0	61.0
Potatoes (8300 lb. dry wt.)	11.5	21.5
Meadow hay (2822 lb. dry wt.)	11.3	12.3

[1] Hart, E. B., and Peterson, W. H. Sulphur requirements of farm crops in relation to the soil and air supply. Wis. Agr. Exp. Sta., Research Bul. No. 14. 1911.

They then call attention to the quantities of sulfur trioxide contained in average soils which, as shown by Hilgard, are less than the quantities of phosphorus pentoxide.

	Quantity in Pounds to the Acre	
	SO_3	P_2O_5
Sandy soils	1650	2610
Clay soils	3250	4280

To ascertain whether the supply of sulfur in the soil is really depleted by cropping, the same authors made parallel determinations of sulfur in five virgin soils and in five soils of the same respective types that had been cropped for sixty years. In each type the cropped soil contained less sulfur than the virgin soil, the average for the cropped soils being .053 per cent SO_3 and for the virgin soils .065 per cent SO_3.

There is no doubt that the quantity of sulfur carried down by rain and snow is much less than that removed in drainage water. There can be no question therefore that most soils, and especially cultivated soils, are losing more sulfur than they receive by natural processes.

It has been customary to add to soils manures of one kind or another that contain more or less sulfur. Among these are farm manure and other animal or bird excrements, residues of crops, animal offal, gypsum or land plaster, superphosphate, ammonium sulfate, potassium sulfate, kainit, and the like, all of which contain consequential quantities of sulfur. It seems probable that

any system of soil management that does not include one or more of these substances would probably, on some soils at least, be improved by making provision for the application of sulfur in some form.

CATALYTIC FERTILIZERS

The term catalytic fertilizers has been used rather loosely to designate a class of substances that, when added to a soil, increase plant growth by apparently accelerating the processes that normally take place in soils. They do not function as fertilizers because their value does not lie in the nutrients that they possess, but they may properly be classed as soil amendments. However, substances not classed as catalyzers, such as lime, have such action, and in all probability most of the fertilizers do also, so that it is difficult to draw any definite distinction and the term will doubtless be used only temporarily.

446. Nature of catalytic action. — The term catalysis is employed in a chemical sense to mean a change brought about in a compound by an agent that itself remains stable. As an example of this may be cited the part that hydrochloric acid plays in the inversion of cane sugar, the acid not entering into the reaction but by its presence greatly accelerating it. When an attempt is made to study these phenomena in soils, it becomes difficult, owing to the multiplicity of factors and reactions, to determine whether the agent is acting in a purely catalytic manner.

447. Catalytic action of soils. — Most soils themselves act as catalyzers in so far as they hasten the decomposition of hydrogen peroxide. Many substances, both organic and inorganic, have this property, and it is not necessarily

entirely lost to the soil after the organic matter has been destroyed by ignition. It is therefore not due to an enzyme, as stated by König, Hasenbäumer, and Coppenrath,[1] who first investigated the subject, nor entirely to organic substances in the soil. Doubtless there are several, or perhaps many, activating substances any of which have this property. It is altogether likely that other catalyzers exist in soils, and that they affect various reactions that are concerned in plant production. Among these substances, as pointed out by König, Hasenbäumer, and Coppenrath,[2] are manganese and iron oxides, which are well known to exert catalytic action on certain reactions. While soils naturally possess certain catalytic powers, it seems possible to still further activate some soils by proper applications of so-called catalytic fertilizers.

Organic matter is doubtless concerned in the catalytic properties of soils, and the investigators just mentioned found that in six soils the catalytic action stood in almost direct relation to the humus content; Sullivan and Reid,[3] however, did not find this correlation to hold. Both organic and inorganic substances are involved in this property of soils, but the forms in which they operate are not well understood. In the main productive soils have a strong catalytic effect and very poor soils are weak in this respect, but this correlation also is not constant.

[1] König, J., Hasenbäumer, J., and Coppenrath, E. Einige Neue Eigenschaften des Ackerbodens. Landw. Vers. Stat., Band 63, Seite 471–478. 1905–1906.

[2] König, J., Hasenbäumer, J., and Coppenrath, E. Beziehungen zwischen den Eigenschaften des Bodens und der Nährstoffaufnahme durch die Pflanzen. Landw. Vers. Stat., Band 66, Seite 401–461. 1907.

[3] Sullivan, M. X., and Reid, F. R. Studies in Soil Catalysis. U. S. D. A., Bur. Soils, Bul. 86. 1912.

448. Substances used as catalytic fertilizers. — A large number of substances have been found to act as catalytic fertilizers. Among these are various salts of manganese, iron, aluminium, zinc, lead, copper, nickel, cobalt, uranium, boron, cerium, lanthanum, and the like. These substances stimulate plant growth when used in small quantities, and are toxic in large amounts. In water cultures a much less quantity of any of them is required to produce an injurious action on plant growth than when applied to an equal volume of soil. The absorptive properties of the soil and the less ready diffusibility serve to mitigate the toxic action.

Different kinds of plants respond differently to the same concentration of any of these substances. For instance, Montemartini[1] found that uranium, copper, zinc, aluminium, and cadmium oxides retard the germination of beans and accelerate the germination of maize when used in equal concentrations.

Of the various plant stimulants mentioned, manganese is the only one that gives promise, at the present time, of usefulness on a commercial basis, and it is the only one that will receive separate treatment in this book.

449. Manganese. — It seems probable that all soils contain manganese, but the quantity present in some soils is very small, often being less than 0.01 per cent; in other soils, however, more than 1 per cent is found, and Kelly[2] reports an Hawaiian soil containing 9.74 per

[1] Montemartini, L. Quoted with other experiments on this subject by N. H. J. Miller, in Annual Reports on the Progress of Chemistry, Vol. 10, pp. 224–230. 1914.

[2] Kelly, W. P. The Influence of Manganese on the Growth of Pineapples. Jour. Indus. and Eng. Chem., Vol. 1, p. 533. 1909.

cent of Mn_3O_4. Sullivan and Robinson [1] examined twenty-six American soils and found the content of MnO to vary from 0.01 to 0.58 per cent, the average being 0.071 per cent.

Manganese is a universal constituent not only of soils, but likewise of plants grown under natural conditions; in plants the quantities present vary much more than in soils, and range from a few tenths of one per cent to nearly one-half of the total ash. However, plants may be produced in water cultures or other media in which apparently no manganese is present and a normal growth and fructification will follow. It is evident, therefore, that any benefit to plant growth that may accrue through the addition of manganese to the soil is not due to its function as a nutrient material in the sense in which nitrogen, potassium, and phosphorus act in that capacity.

450. **Physiological rôle of manganese.** — It was the discovery by Bertrand [2] of the existence of manganese in the oxidizing enzymes of plants and of its function in stimulating the oxygen-carrying power of these catalytic agents that suggested its use as a stimulating agent in crop production. In water cultures a very dilute solution of manganese salts increases plant growth, but beyond a very low concentration its effect is toxic. Plants differ widely in their response to manganese, with respect both to stimulation and to injury. A certain concentration may be stimulating to one plant, and toxic to another.

Experiments in the application of manganese salts

[1] Sullivan, M. X., and Robinson, W. O. Manganese as a Fertilizer. U. S. D. A., Bur. Soils, Circ 75. 1913.

[2] Bertrand, G. Sur l'Action Oxydante des Sels Manganeux et sur la Constitution Chimique des Oxydases. Compt. Rend. Acad. Sci. Paris, Tome 124, pp. 1355–1358. 1897.

to soils have not afforded as satisfactory results as have the trials with water cultures. Applications of a certain salt of manganese, when applied at the same rates to different soils, have in some cases produced increased growth, have in other cases had no apparent effect, and have in still other cases proved injurious to plants. The reason for this is doubtless to be found in the inherent properties of the particular soil to which the application is made.

451. Action of manganese as a fertilizer.—The fact that manganese stimulates plant growth in water cultures is very good evidence that it has at least a direct action on the plant. Whether it has a further influence through reactions brought about in the soil is less evident, although it seems likely that such is the case. Thus, Skinner and Sullivan[1] conclude from some of their experiments that oxidation in some soils is increased by the application of manganese salts. It also seems probable that manganese may have some influence on the activity of the microörganisms of the soil, but this has not been definitely demonstrated.

452. Forms of manganese and response of soils.—The manganese salts that have been found to be effective as fertilizers are the sulfate, the chloride, the nitrate, the carbonate, and the dioxide. Of these the first has been most generally used, and in quantities up to 50 pounds an acre it has in most cases not been toxic. On acid soils it is not supposed to exercise any beneficial action, and on very productive soils Skinner and Sullivan, in the experiments cited above, found it to be ineffective;

[1] Skinner, J. J., and Sullivan, M. X. The Action of Manganese in Soils. U. S. D. A., Bul. 42. 1914.

while they obtained appreciable benefit from its use on poor soils. They argue that since very productive soils have great oxidative power the use of manganese is unnecessary, but since poor soils undergo insufficient oxidation the stimulation that this process receives by the application of manganese is productive of much good. Accordingly manganese is most profitably used on poor soils not deficient in lime.

CHAPTER XXIV

SOIL AMENDMENTS

Certain substances are sometimes added to soils for the purpose of increasing productiveness through their influence on the physical structure of the soil, and thereby on the chemical and bacteriological properties. These substances are called soil amendments. It is true that they may add essential plant ingredients to the soil, but that function is of minor importance.

463. Salts of calcium. — Calcium, although essential to plant growth, seldom needs to be added to the soil to supply the plant directly; but because of its effect on the soil properties, its use is beneficial to a great number of soils.

464. Effect on tilth and bacterial action. — On clay soils the effect of lime is to bring the fine particles into aggregates which are loosely cemented by calcium carbonate. The effect of this structure on tilth has already been explained (par. 120). On sandy soils the carbonate of calcium serves to bind some of the particles together, making the structure somewhat firmer and increasing the water-holding power. It should be used only in small quantities on sandy soils.

There is a tendency for most cultivated soils to become acid, as has already been explained (par. 283). Acidity may reach a point where it becomes directly injurious to certain plants, but it becomes indirectly injurious before

that point is reached. One way in which this occurs is by curtailing the quantity of calcium carbonate in the soil. An easily available base to combine with the organic acids affords the most favorable condition for the decomposition processes due to bacterial action, and hence the best results cannot be obtained where carbonate of lime is not present. Its action in improving tilth also facilitates desirable forms of bacteriological activity by increasing the permeability of the soil for air.

450. Liberation of plant-food materials. — It has been stated that the alkalies and the alkaline earths are more or less interchangeable in certain compounds in the soil. The addition of lime may in this way liberate potassium, when otherwise it would be difficult for crops to obtain a sufficient supply from a particular soil. The substitution of bases has been discussed (par. 251) and the liberation of potassium is in accord with these phenomena. Magnesium, although rarely deficient, may also be made available in this way. The use of calcium salts may, under some soil conditions, render phosphorus more useful, probably by supplying a base more soluble than iron or alumina, with which, in soils deficient in calcium, the phosphorus might otherwise be combined. Experiments by Prianischnikov,[1] in which plants were grown in washed sand containing Hellriegel's nutrient solution to which mono-, di-, and tri-calcium phosphate respectively were added, both with and without calcium carbonate, showed a decreased availability of the tricalcium phosphate due to the presence of the carbonate, but neither a reduced nor an increased availability of the other forms of phos-

[1] Prianischnikov, D. Ueber den Einfluss von Kohlensaurem Kalk auf die Wirkung von Verschiedenen Phosphaten. Landw. Vers. Stat., Band 75, Seite 357-376. 1911.

phorus arising from the presence of carbonate. Neither did the availability of iron or aluminium phosphate appear to be influenced by calcium carbonate.

These and recent experiments by Simmermacher[1] and others tend to discredit the earlier conclusions as quoted above and as set forth by Dehérain[2] regarding the favorable influence of lime on the availability of phosphorus. However, the preponderating evidence is still with the earlier experimenters. The principles that underlie the effect of lime on availability of phosphorus are discussed in paragraphs 259 and 260.

366. Influence of lime on the formation of nitrates in soil. — It has already been remarked that nitrification proceeds very slowly in acid soils. A soluble base must be present with which the nitric acid may combine, otherwise the process will be inhibited by the toxic effect of the acid on the bacteria concerned in the formation of the acid. The addition of lime is the most economical method of providing the base. This is often a matter of great moment for crops that respond readily to nitrate nitrogen, and is one of the important reasons for applying lime to sour soils. The fact that some plants grow better in sour soils than in strongly basic ones is also an indication that such plants absorb a considerable part of their nitrogen in forms other than nitrates.

Many investigators have found that the presence of calcium carbonate promotes the ammonifying and nitrifying process. The addition of calcium carbonate to a

[1] Simmermacher, W. Die Wirkung des Kohlensauren Kalkes bei der Düngung von Haferkulturen mit Mono- und Dicalcium Phosphat. Landw. Vers. Stat., Band 77, Seite 441–471. 1912.

[2] Dehérain, P. P. Traité de Chimie Agricole, p. 526. 1892.

sandy loam soil was found by Kellerman and Robinson[1] to favor the formation of nitrates up to an application of 2 per cent, which is much more than would ever be applied in practice. It must be kept in mind, however, that this limit does not apply to all soils, as the absorptive properties of the soil for lime will determine the maximum application that may profitably be made. Kellerman and Robinson found also that the application of magnesium carbonate in excess of 0.25 per cent inhibited the formation of nitrates. Kelly[2] also has recently reported that the addition of magnesium carbonate to the soils with which he experimented resulted in a marked depression of both ammonification and nitrification, and that the addition of calcium carbonate did not overcome this depressing influence.

457. **Effect on toxic substances and plant diseases.** — Free acids are toxic to most agricultural plants. Some plants are much more sensitive than others. Alfalfa, for example, should have a slightly alkaline medium for its best growth, and any acid is very injurious. Calcium salts, in neutralizing acidity, remove this toxic condition. A liberal application of lime is therefore a precaution against injury of this kind.

The presence of soluble calcium, with its effects on the soil, retards the development of certain plant diseases, such as the "finger and toe" disease of the Cruciferæ. On the other hand, it may promote some diseases, as, for example, potato scab.

[1] Kellerman, K. F., and Robinson, T. R. Lime and Legume Inoculation. Science, n. s., Vol. 32, pp. 159-160. 1910.

[2] Kelly, W. P. The Effects of Calcium and Magnesium Carbonates on Some Biological Transformations of Nitrogen in Soils. Univ. of Calif. Pub., Agr. Sci., Vol. 1, No. 3, pp. 39-49. 1912.

468. The lime-magnesia ratio. — The physiological balancing of magnesium by calcium was first worked out by Loew,[1] and the ratio in which these two cations should exist in nutrient solutions in order to secure the best growth of certain agricultural plants has been very satisfactorily demonstrated by the experiments of many investigators. The optimum ratio varies with different kinds of plants, and in general the calcium must exceed the magnesium in amount, but there is a limit beyond which it should not be present. If calcium alone is present, it acts as a toxic agent on the plant, and magnesium acts in a similar way. It is only when the ratio between these cations falls within certain limits that they exert no toxic action. This ratio varies between one part of calcium oxide to one part of magnesium oxide, and seven parts of calcium oxide to one part of magnesium oxide.

In the soil the relations of calcium and magnesium to plant growth are not so simple. It is impossible to determine the actual or the relative quantities of these cations that are available for absorption by the plant. This is mainly because of the absorptive properties of soils, by which they remove the bases from solution and hold them in a somewhat difficultly soluble form. The ratio of calcium to magnesium is not likely to disturb crop yields in soils unless the quantity of magnesium present happens to be very large. Gile and Ageton[2] have found ordinarily fertile soils having ratios as high

[1] Loew, O. The Physiological Rôle of the Mineral Nutrients of Plants. U. S. D. A., Bur. Plant Indus., Bul. 1, p. 53. 1901.

[2] Gile, P. L., and Ageton, C. N. The Significance of the Lime-Magnesia Ratio in Soil Analyses. Jour. Indus. and Eng. Chem., Vol. 5, pp. 33–35. 1913.

as 500 CaO to 1 MgO by weight. On the other hand, excessive applications of magnesium compounds have been found to be injurious on some soils. Even on a very heavy clay soil, at Cornell University, an application of 1333 pounds to the acre of magnesite markedly decreased the yields of sorghum and oats. The soil originally contained about equal parts of calcium and magnesium.

459. Forms of calcium. — Calcium is used on the soil in the form of calcium oxide, or quicklime (CaO), water-slaked lime ($Ca(OH)_2$), air-slaked lime ($CaCO_3$), ground limestone, marl (also a carbonate), and calcium sulfate, or gypsum ($CaSO_4 \cdot 2H_2O$). The application of any of these is usually called liming the soil, although gypsum does not serve exactly the same purpose as do the other forms. Owing to differences in the molecular weights of these compounds of calcium, it requires more of some forms than of others to furnish the same amount of calcium. Approximately equivalent quantities of some of the common forms when fairly pure are, —

Quicklime	56 pounds
Water-slaked lime	74 pounds
Air-slaked lime, marl, and ground limestone	100 pounds

Quicklime, and the hydrate, when added to the soil, eventually assume some of the more insoluble forms of combination or remain as the carbonate, never being present as the oxide. It is always desirable to have present in the soil at least a small amount of calcium carbonate.

460. Caustic limes. — Quicklime and water-slaked lime have a markedly alkaline reaction, and hence neutralize quickly any active acidity that may exist in the soil. They act quickly also in liberating plant-food, particularly

nitrogen. Some soils respond more rapidly to quicklime or water-slaked lime than to carbonate of lime, especially when the carbonate is in the form of marl or ground limestone, these substances never being in such a finely pulverized condition as is caustic lime. The use of the caustic forms of lime has been said to result in the loss of nitrogen by the too rapid decomposition of organic compounds.

On clays the granulating effect of caustic lime is more marked than that of the carbonate, and for this reason the former has a distinct advantage for use on heavy clay. For the same reason an occasional moderate dressing is better than a heavy dressing given less frequently.

481. Carbonate of lime. — Air-slaked lime has the advantage of being in a finely divided condition, and does not produce the injurious action on organic matter that is sometimes attributed to caustic lime. Its effect on the granulation of clay soils is probably less pronounced than that of caustic lime.

Marl (par. 27) differs from air-slaked lime principally in its property of being in a less finely pulverized condition. It acts less quickly than does caustic lime. Owing to the fact that marl deposits differ greatly in the composition of their products, it is well to know the quality of the material before buying it. The carbonate of lime in marl may vary from 5 or 10 to 90 or 95 per cent in different samples.

Ground limestone has been used extensively in recent years. It is very important that it be finely ground, as on the comminution of the material much of its efficiency depends. However, it is doubtful whether there is any advantage in making it finer than is required to pass through a sieve with 50 meshes to the inch.

408. Relative effectiveness of caustic lime and carbonate.—In order to test the value of ground limestone and other forms of calcium carbonate, experiments in which it was compared with caustic lime have been conducted at some of the experiment stations. Reports of tests at the Pennsylvania Experiment Station,[1] in which plats treated with slaked lime at the rate of two tons per acre once in four years were compared with plats treated with ground limestone at the rate of two tons to the acre every two years, show that at the end of twenty years, in every case, the total yields were greater on the plats receiving ground limestone. After the treatment on these plats had been continued for sixteen years, a determination of nitrogen showed the upper nine inches of soil on the limestone treated plats to contain 2979 pounds of nitrogen to the acre, and the slaked-lime plats to contain 2604 pounds. It may be inferred from these figures that the slaked lime caused a slightly greater destruction of organic matter than did the limestone.

Patterson[2] also conducted experiments for eleven years with caustic lime produced by burning both stone and shells, and the carbonate of lime in ground shells and shell marl. The average crops of maize, wheat, and hay were all larger on the plats treated with carbonate of lime.

While these experiments show, at first glance, results

[1] Waters, H. J., and Hess, E. H. General Fertilizer Experiments. Pennsylvania State College, Rept. 1904, Part 2, pp. 258-281. Also, Hunt, T. F. Soil Fertility. Pennsylvania Agr. Exp. Sta., Bul. 90. 1909.

[2] Patterson, H. J. Lime, Sources and Relation to Agriculture. Maryland Agr. Exp. Sta., Bul. 66, pp. 127-139. 1900. Also, Investigations on the Liming of Soils. Maryland Agr. Exp. Sta., Bul. 110, pp. 16-21. 1906.

rather favorable to the use of carbonate of lime, a careful analysis of them by Wheeler[1] raises some doubt as to the legitimacy of this interpretation. He points out, for instance, that in the Pennsylvania experiments excessive quantities of lime were used, and that no farm manure nor commercial fertilizers were applied to the plats between which comparisons were made.

There is, unfortunately, a paucity of definite and conclusive data that may be applied to the solution of the question as to the relative values of these different forms of lime for use as soil amendments, but some information has accumulated through experience and practice that may be taken as a fairly safe guide in their use. It is well known, for instance, that burned lime has a more pronounced effect on soil granulation than has the carbonate, and may therefore be expected to be more beneficial to heavy clay soils. On the other hand, burned lime is not so desirable a form to apply to very sandy soils, especially when they are likely to be dry, as there is danger that organic matter will be destroyed.

463. **Sulfate of calcium.** — Gypsum, in which form calcium sulfate is usually applied to soils, has been used for many years and was a popular soil amendment in this country before the common commercial fertilizers were used to any great extent. It frequently went by the name of *land plaster*, and, as it was rather widely distributed in nature and not difficult to obtain, it was ground and largely used in many localities throughout the eastern states. Its popularity has waned in recent

[1] Wheeler, H. J. Is the Recommendation that Only Ground Limestone Should be Used for Agricultural Purposes a Sound and Rational One? National Lime Manufacturers' Assoc., Bul. 4. 1912.

years, and its effectiveness has apparently decreased as the soils on which it was used have been longer under cultivation. Possibly this is due to the tendency of these soils to become more acid, which has caused the gypsum to be less effective in liberating potassium — a property with which it has generally been credited. At present gypsum is not very generally used on soils. It must be remembered, however, that superphosphates always contain a considerable proportion of this material, and it may add appreciably to the beneficial effects of that fertilizer.

Aside from its action in liberating potassium (the actual extent of which has never been very clearly demonstrated), gypsum serves to supply sulfur to the soil. The sulfur, while it may be needed in some soils, has the disadvantage of being present as an acid, and if the acid is added in larger quantity than is removed by plants there is a resulting loss of basic material in the drainage water and a tendency for the soil to become sour.

The action of gypsum in improving tilth is less marked than that of caustic lime or of the carbonate. As a source of calcium it is of no moment, as, if applied in such quantities as those in which the other forms are used, the sulfate would be very injurious. Ordinarily it is applied at the rate of only a few hundred pounds to the acre at the most. On the whole, gypsum is not an adequate substitute for, nor so desirable a form of, calcium as the oxide, the hydroxide, or the carbonate.

484. Common salt. — Sodium chloride has a marked effect on some soils, but wherein its effectiveness lies is not well understood. The addition of sodium and of chlorine as plant constituents is clearly not the reason, as these substances are always present in soils in available form far in excess of their requirements.

The effect of sodium chloride on clay-bearing soils is to liberate certain plant nutrients, among which are calcium, magnesium, potassium, and phosphorus. This action, although limited in amount, is probably, in some cases at least, partly responsible for the beneficial action of common salt.

The structure of the soil is improved by the application of sodium chloride, just as it is by lime, although usually not to the same extent.

Another effect of salt is to conserve and distribute soil moisture. Its conserving action is probably due to an increase in the density of the soil-water solution, thus retarding transpiration. The film movement of water is likewise increased by the presence of salt in the solution, and in this way the upward movement of bottom water is facilitated and the supply within reach of the roots maintained in time of drought.

It has been seen that sodium is not one of the substances essential to the growth of plants. But that sodium may be substituted, in part, for the potassium absorbed by agricultural plants in their normal growth, has been shown in this country by the experiments of Wheeler and Adams;[1] and the more ready availability of the sodium applied as a chloride than of the potassium in its natural condition in some soils probably accounts in part for the beneficial effects of this salt.

It is not all soils, however, that are benefited by salt, its usefulness not being of such wide application as that of lime. Certain crops, as previously mentioned, are injured by the presence of chlorine.

[1] Wheeler, H. J., and Adams, G. E. Concerning the Agricultural Value of Sodium Salts. Rhode Island Agr. Exp. Sta., Bul. 106. 1905.

468. **Muck.**—The effect of muck (par. 72) is to change the structure of soils, making a heavy clay soil lighter and more porous, and binding together the particles of a sandy soil. Both classes of soils, but particularly the sandy type, have a greater water-holding capacity after treatment with muck, owing to its great absorptive power which amounts to 70 per cent or more of its own weight. It is to its content of organic matter that the physical effects of muck are due.

Muck contains 1 to 2 per cent of organic nitrogen, calculated to dry matter, which does not readily undergo ammonification. The addition of farm manure (which ferments readily) and of lime serves to hasten ammonification. Its use as an absorbent in the stable fits it well for use on the land.

Very large applications of muck are necessary when it is used to improve the structure of the soil. From ten to forty or fifty tons per acre are frequently applied.

Muck has been used successfully as a carrier of *Bacillus radicicola*; for this it is eminently adapted by its absorbent qualities, which prevent it from drying out and thus causing injury to the bacteria. At the rate of thirty pounds to the acre it has served as a highly effective medium for inoculating soil for alfalfa.[1]

Muck is also used as a filler in certain commercial fertilizers.

[1] Lyon, T. L., and Bizzell, J. A. Some Experiments in Top-Dressing Timothy and Alfalfa. Cornell Univ. Agr. Exp. Sta., Bul. 339. 1913.

CHAPTER XXV

FERTILIZER PRACTICE

THE purchase and use of commercial fertilizers in an economical way requires not only specific technical knowledge of the various materials, as already set forth, but also a certain amount of general knowledge both practical and theoretical. There are at present so many fertilizing materials on the market under various trade names, that the question as to the best one to buy for a certain crop growing under definite soil and climatic conditions becomes a difficult one. The greater the general knowledge, therefore, that a person possesses as to the effects of the different elements on plant growth, as to fertilizer inspection and control, as to methods of buying, as to home mixing, as to methods and time of application, and as to mixtures for special crops, the better he is able to utilize fertilizers that will result in financial gain. That a fertilizer shall be profitable is the ultimate desideratum. Moreover, as all fertilizers exert, either directly or indirectly, a residual effect, the problem necessarily broadens into a study of the systems of applying fertilizers to a series of crops or to a rotation, rather than a study of the effects of one particular fertilizer application on one particular crop.

Note. — For discussions of fertilizer practice see Halligan, J. E., Soil Fertility and Fertilizers, Chapters 13–17. Easton, Pennsylvania. 1912. Also, Van Slyke, L. L. Fertilizers and Crops, Chapters 21–25, and 27–35. New York, 1912. Also, Fraps, G. S. Principles of Agricultural Chemistry, Chapter 16. Easton, Pennsylvania. 1913.

268. Effects of nitrogen on plant growth.[1] — Of the three primary elements of a fertilizer, nitrogen[2] seems to have the quickest and most pronounced effect, not only when present in excess of the other constituents, but also when moderately used. It tends primarily to encourage aboveground vegetative growth and to impart to the leaves a deep green color, a lack of which is usually due to insufficient nitrogen. It tends in cereals to increase the plumpness of the grain, and with all plants it is a regulator in that it governs to a certain extent the utilization of potash and phosphoric acid. Its application tends to produce succulence, a quality particularly desirable in certain crops. In its general effects it is very similar to moisture, especially when supplied in excessive quantities.

The peculiarity of nitrogen lies not only in its absolute necessity for plant growth, its stimulation of the vegetative parts, and its close relationship to the general tone and vigor of the crop, but also in the fact that it was not one of the original elements of the earth's crust. During the formation of the soil it slowly and gradually became present, brought down by rains and fixed naturally in the soil itself mostly through the agency of bacterial action. Even now it exists largely locked up in complex nitrogenous compounds of the humus and the less decayed organic matter, and becomes slowly available to plants

[1] Discussions of the effects of the various elements on plants may be found as follows: Russell, E. J. Soil Conditions and Plant Growth, Chapter II, pp. 19–30. London, 1912. Also, Hall, A. D. Fertilizers and Manures, Chapters III, V, and VI. New York, 1910.

[2] For a discussion of nitrogen in relation to crop yield, see Hunt, T. F. The Importance of Nitrogen in the Growth of Plants. Cornell Univ. Agr. Exp. Sta., Bul. 247. 1907.

largely through bacterial activity. It may be stated with certainty that one of the possible limiting factors to crop growth is a lack of water-soluble nitrogen at critical periods in amounts necessary for normal crop development. Since soluble nitrogen may be very readily lost from the soil by leaching, the problem of proper plant nutrition becomes a serious one. Not only must the farmer be able to so regulate its addition in fertilizers as to obtain the highest efficiency, but he must understand the control and encouragement of the natural fixation as well. The emphasis placed on all phases of the nitrogen problem serves to reveal its great importance in fertility practices.

Because of the immediately visible effect from the application of soluble nitrogen, the average farmer is prone to ascribe too much importance to its influence in proper crop development. This attitude is unfortunate, since nitrogen is the highest-priced constituent of ordinary fertilizers. Moreover, of the three primary elements it is the only one which added in excess will result in harmful after effects on the crop. Its general influences, besides its functions in the metabolic and synthetic processes of plant development, may be listed briefly as follows:

1. *Nitrogen tends to increase the growth of the above-ground parts.*
2. *It delays maturity* by encouraging vegetative growth. This oftentimes endangers the crop to frost, or may cause trees to winter badly.
3. *It increases the ratio of straw to grain* in cereals, and the ratio of leaves to underground parts in root crops.

4. *It weakens the straw and causes lodging in grain.* This is due to an extreme lengthening of the internodes, and as the head fills the stem is no longer able to support the increased weight.
5. *It lowers quality.* This is especially noticeable in certain grains and fruits, as barley and peaches. The shipping qualities of fruit and vegetables are also impaired.
6. *It increases the percentage of nitrogen in the crop,* particularly in the straw of cereals and in timothy hay.
7. *It decreases resistance to disease.* This is probably due to a change in the physiological resistance to disease within the plant, and also to a thinning of the cell wall, allowing a more ready infection from without.

While certain plants, as the grasses, lettuce, radishes, and the like, depend for their usefulness on plenty of nitrogen, for the average crop it is generally better to limit the amount of nitrogen so that growth may be normal. This results in a better utilization of the nitrogen and in a marked reduction of the fertilizer cost for a unit of crop growth. This is a vital factor in all fertilizer practice, and shows immediately whether fertilization is or is not an economic success.

467. Effects of phosphorus on plant growth.—It is difficult to determine exactly the functions of phosphoric acid in the economy of even the simplest plants. Neither cell division nor the formation of fat and albumen go on to a sufficient extent without it. Starch may be produced when it is lacking, but will not change to sugar. As grain does not form without its presence, it very probably is concerned in the production of nucleoproteid

materials. Its close relationship to cell division may account for its presence in seeds. Its general effects on plant growth may be listed as follows:

1. *Phosphorus hastens maturity by its effect on rate of ripening.* This makes phosphorus especially valuable in wet years, and in cold climates where the season is short.
2. *It increases root development,* especially of lateral and fibrous rootlets. This renders it valuable with such soils as do not encourage root extension and to such crops as naturally have a restricted root development. Phosphorus is therefore valuable in fall-sown crops, in years of drought, and for farming on arid land.
3. *It decreases the ratio of straw to grain* by hastening the filling of the grain and by promoting maturity.
4. *It strengthens the straw,* due to its balancing effect on the nitrogen.
5. *It improves the quality of the crop.* This has been recognized in the handling of pastures in England and France. The effect on vegetables is also marked.
6. *It increases percentage of phosphorus in the crop.* With cereals this is particularly noticeable in the straw.
7. *It increases resistance to disease,* due probably to more normal cell development.

Excessive phosphorus ordinarily has no bad effect, as it does not stimulate any part excessively as does nitrogen, nor does it lead to a development which is detrimental. Its lack is not quickly apparent, as in the case

of nitrogen, and as a consequence phosphorus starvation may occur without any suspicion thereof being entertained by the farmer.

One of the most important phases to be noted from this comparison of the effects of nitrogen and phosphorus is the balancing powers of the latter on the unfavorable influences generated by the presence of an undue quantity of the former. This is a vital factor in fertilizer practice, since normal fertilizer stimulation always results in the most economic gains. Such a normal increase is obtained only when the plant functions of the several fertilizer constituents are in proper accord.

468. Effects of potassium on plant growth. The effects of potash are more localized than those of nitrogen and phosphorus. Potash is essential to starch formation, either in photosynthesis or in translocation, and is a necessary component of chlorophyll. It is important in grain formation, giving plump, heavy kernels. In general it tends to impart tone and vigor to a plant. In increasing resistance to disease it tends to counteract the ill effects of too much nitrogen, while in delaying maturity it works against the ripening influences of phosphoric acid. In a general way it exerts a balancing effect on both nitrogen and phosphate fertilizer materials, and consequently is necessary in a mixed fertilizer, especially if the potash of the soil is lacking or unavailable. As with phosphorus, it may be present in large quantities in the soil and yet exert no harmful effect on the crop.

469. Law of the minimum. — In connection with the obvious importance of utilizing, for any particular soil and crop, a fertilizer well balanced as to the three primary elements, two queries naturally arise. These are:

(1) What are the right proportions of nitrogen, phosphorus, and potash to apply under given conditions? (2) What would be the effect if any one of these should not be present in such a quantity as to make it equal in function to the others? The first query cannot be disposed of until the question of fertilizer mixtures has been considered. The second, however, is not affected by so many factors, and is more clearly a question of the function of the elements concerned.

Any element that exists in relatively small amounts as compared with the other important constituents naturally becomes the controlling factor in crop development. Any reduction or increase in this element will cause a corresponding reduction or increase in the crop yield. This element, then, is said to be "in the minimum." In fertilizer practice, ideal conditions would exist if no constituent functioned as a decided minimum and the entire influence of each single element were fully utilized. In other words, the fertilizer would be balanced as to its relationship to normal plant growth. That such a condition is more or less ideal and theoretical is obvious, from the fact that the various fertilizer carriers undergo more or less radical changes after being applied to the soil. The composition of the soil itself is also a disturbing factor. Nevertheless, the nearer an approach can be made to such conditions, the greater will be the economy of fertilizer practice.

Numerous persons have investigated the question as to what effect an increase of an element in the minimum may have on crop yield, and various ideas have been advanced thereon. The idea of a definite law governing the increase of plant growth according as the element in the minimum is increased, was first suggested by

Liebig. Wagner[1] later stated definitely that up to a certain point the increase yield was proportional to the increase in the application. This, however, evidently cannot apply except over a very limited field, since it is a matter of common observation that increased crop yield becomes lower as the lacking element is supplied. Recently Mitscherlich[2] has formulated a law[3] which is a logarithmic, rather than a direct, function of the increase in the element occupying the position of the minimum. Mitscherlich's law may be stated concisely as follows: the increased growth produced by a unit increase of the element in the minimum is proportional to the decrement from the maximum. The following curve (see Fig. 62) constructed from data obtained by Mitscherlich,[4] shows the trend of the increased growth curve as governed by increased applications of an element in the minimum, other factors being, of course, under control. This curve is maintained by Mitscherlich to approximate a theoretical curve of a definite mathematical formula.

[1] Wagner, P. Beiträge zur Düngerlehre. Landw. Jahr., Band 12, Seite 691 ff. 1883.

[2] Mitscherlich, A. E. Das Gesetz des Minimums und das Gesetz des Abnehmenden Bodenertrages. Landw. Jahr., Band 38, Seite 537–552. 1909.

Also, Ein Beitrage zur Erforschung der Ausnutzung der im Minimum Vorhandenen Nährstoffe durch die Pflanze. Landw. Jahr., Band 39, Seite 133–156. 1910.

[3] $\frac{dy}{dx} = (a - y)k$. Integrating, $\log (a - y) = c - kx$.

y = total yield from any number of increments.

x = amount of any particular fertilizer constituent utilized.

a = maximum yield and is a constant.

k = a constant depending on y and x, variables.

[4] Mitscherlich, A. E. Über das Gesetz des Minimums und die sich aus diesem Ergebenden Schlussfolgerungen. Landw. Ver. Stat., Band 75, Seite 231–263. 1911.

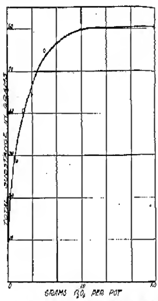

Fig. 62.—Curve showing the increased growth of oats under the influence of constantly increasing amounts of phosphorus, that element being in the minimum.

The formula as proposed by Mitscherlich has been questioned by several investigators,[1] who have shown that a number of conditions, such as light, heat, and

[1] Pfeiffer, Th., Blanck, E., and Flügel, M. Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze vom Minimum. Landw. Ver. Stat., Band 78, Seite 211-223. 1912.
Also, Mazé, P. Recherches sur les Relations de la Plante

moisture, tend to disturb the application of such a law. The fact that crop yield is the summation of so many varying factors seems to argue in favor of no hard and fast rule regarding the increased growth due to the added increments of an element in the minimum. It is enough, in the practical utilization of fertilizers, to remember that this curve in general approximates the one already cited, and that in order to obtain the best results from a complete fertilizer a mixture should be used that is approximately balanced so far as the effects of the elements are concerned, the crop as well as the chemical constitution of the soil being considered.

470. Fertilizer brands. — In an attempt to meet the demands for well-balanced fertilizers suited to various crops and soils, manufacturers have placed on the market numberless brands of materials containing usually at least two of the important elements, and nearly always the three; the former being designated as incomplete fertilizers, while the latter are spoken of as complete fertilizers. These various brands usually have some catchy name, such as "The Ureka Corn Special," "Farmers' Potato and Corn Fertilizer," "The Golden Harvest," or "The Empire State Sure Crop Phosphate." Such a name frequently implies the usefulness of the material for some particular crop, but oftener it has no relation either to crop or to soil. Ordinarily the name should be ignored in the purchase of fertilizers.

A brand of fertilizer is usually made up of a number of materials containing the important ingredients. These materials, already described, are called carriers. The making-up of a commercial fertilizer consists, then, in

avec les Elements Nutritifs du Sol. Compt. Rend., Vol. 154, pp. 1711–1714. 1912.

merely mixing the various carriers together so that the required percentages of nitrogen, potash, and phosphoric acid are obtained, care being taken that no detrimental reaction shall occur and that a physical condition consistent with easy distribution shall be maintained. If the substances used are difficultly soluble, the fertilizer is not so valuable as one composed of easily soluble constituents. The general solubility of the various ingredients should be known by a prospective purchaser.

The various brands on the market, besides being complete or incomplete, may be designated as high-grade or low-grade. These terms may be used in two ways — high-grade or low-grade as to availability, or high-grade or low-grade as to amount of plant-food constituents carried. A low-grade fertilizer in the percentages of nitrogen, phosphoric acid, and potash is always encumbered with a large amount of inert material, which adds to the cost of mixing, transportation, and handling. It is thus usually a more expensive fertilizer to a unit of plant-food obtained than one of higher grade. Except for special purposes, a low-grade fertilizer as to availability should be bought sparingly or not at all.

471. **Fertilizer inspection and control.**—With the many different materials available for mixing commercial fertilizers, and from the fact that so many opportunities are open for fraud either as to availability or as to guarantee, laws have been found necessary for controlling the sale of fertilizers. Most states have such a law, the western laws generally being superior to those in force in eastern states, where the fertilizer sale is heavier. This is because the western regulations are more recent and the legislators have had the advantage of the experience gained where fertilizers have long been used.

Moreover, the legislators in such states have not been so strongly confronted with fertilizer lobbying, and have consequently been free to enact stricter laws than were possible where fertilizers are such an important commercial commodity.

Usually certain provisions are common to all fertilizer laws. In general, all fertilizers selling for a certain price or over (usually $5 a ton) must pay a state license fee and print the following data on the bag or on authorised tag: —

1. Number of net pounds of fertilizer to a package.
2. Name, brand, or trade-mark.
3. Name and address of manufacturer.
4. Chemical composition or guarantee.

The composition of a commercial fertilizer is ordinarily expressed simply; for example, as a 3 6 10, meaning 3 per cent of nitrogen, 6 per cent of phosphoric acid, and 10 per cent of potash. This, however, is too brief for a guaranteed analysis on goods exposed for sale, as it gives no idea whatsoever regarding the solubility of the materials. As might be expected, there is a wide range in the character of the guarantee required by the various states. For example, some states insist on the statement of the percentage of both nitrogen and ammonia, while others insist only on the percentage of nitrogen. Some require the soluble, the reverted, and the total phosphoric acid, while others require only the soluble and the reverted. As to potash, in some cases the soluble must be stated, while in other cases the total must be given. In general, a guarantee should show not only the amount of the various constituents, but also their form or availability. The guarantee required by North Dakota is excellent in this respect: —

Guarantee required by the State of North Dakota

Percentage of N in nitrates	Percentage of P_2O_5 soluble in water
Percentage of N as ammonia	
Percentage of N total	Percentage of P_2O_5 reverted
	Percentage of P_2O_5 insoluble
Percentage of K_2O soluble	
Percentage of K_2O as chloride	Percentage of P_2O_5 total

Since a fertilizer law is designed primarily to protect not only the purchasers but also the manufacturers, a certain amount of variation is allowed below a guarantee. This is a matter of extreme variation in the different states. Ordinarily, also, the offering for sale of any leather matter or its products, either separately or in mixtures, is prohibited, unless so stated specifically on the package.

For the enforcement of such laws, the states usually provide adequate machinery. The inspection and analyses may be in the hands of the state department of agriculture, of the director of the state agricultural experiment station, of a state chemist, or under the control of any two of these. In any case, a corps of inspectors is provided, the members of which take samples of the fertilizers on the market throughout the state. These samples are analyzed in laboratories provided for the purpose, in order to ascertain whether the mixture is up to its guarantee. If the fertilizer falls below the guarantee, — allowing, of course, for the variation permitted by law, — the manufacturer is subject to prosecution.

A more effective check on fraudulent guarantees, however, is found in publicity. The state law usually provides for the publication each year of the guaranteed and found analyses of all brands inspected. Not only has

has proved effective in preventing fraud, but it is really a great advantage to the honest manufacturer.

The expenses for the inspection and control of fertilizers are usually defrayed by the license fees, which average for the different states from ten to twenty dollars a year for each brand selling for $5 or more a ton. In the eastern states this fee produces a net return greatly in excess of the expenses incurred by the fertilizer inspection and control, and consequently has become the source of a handsome income for these states.

472. Trade values of fertilizers.—It has become customary for the authorities charged with fertilizer inspection and control in the various states to adopt each year a schedule of the trade values of the various elements as they appear on the market in unmixed lots. These values are obtained by averaging all the wholesale prices of a ton for the various unmixed supplies for the six months preceding March 1, to which is added 20 per cent of the price to cover cost of handling. The trade values for 1912 were as follows:[1]

Trade Values of Plant-food Elements in Raw Materials and Chemicals

	Cents a pound
Nitrogen in ammonia salts	18½
Nitrogen in nitrates	18½
Organic nitrogen in dry and fine fish, meat, and blood	20
Organic nitrogen in fine bone, tankage, and mixed fertilizer	19
Organic nitrogen in coarse bone and tankage	16
Organic nitrogen in castor pomace and cottonseed meal	20

[1] New York (Geneva), Agr. Exp. Sta. Bul. 371, p. 434. 1913.

	Cents a pound
Phosphoric acid, water-soluble	$4\frac{1}{2}$
Phosphoric acid, citrate-soluble (reverted)	4
Phosphoric acid, in fine bone, fish, and tankage	4
Phosphoric acid, in cottonseed meal and castor pomace	4
Phosphoric acid, in coarse fish, bone, tankage, and ashes	$3\frac{1}{2}$
Phosphoric acid in mixed fertilizers, insoluble in water or ammonium citrate	2
Potash as high-grade sulfate, in forms free from chlorides, in ashes, etc.	$5\frac{1}{4}$
Potash as muriate	$4\frac{1}{4}$
Potash in castor pomace and cottonseed meal	5

It must be remembered that these prices are seaboard evaluations, and represent the cost to the manufacturer of the elements as they exist in the unmixed carriers. This is called the commercial evaluation of a fertilizer, and is the first of a number of items that enter into the total cost, or the price the farmer must pay on the retail market. The items that make up this ultimate price may be listed as follows: (1) wholesale cash cost, or commercial evaluation; (2) cost of mixing; (3) profit of manufacturers; (4) transportation; (5) storage, commission to agents, bad debts, and so forth; and (6) profit of retailer. These additional charges are often sufficient to double the original commercial value of the fertilizer constituents.

It is evident that by knowing the composition of a fertilizer, and the carriers of the various constituents, the commercial evaluation of the mixture may be easily calculated. However, what the farmer must pay depends

to a large extent on the additional charges already listed. Thus, a fertilizer evaluated at $22 a ton on the New York market may cost the farmer $35, or even $45, after having passed through the hands of the manufacturer and the retail merchant. This commercial evaluation, however, must not be confused with the agricultural evaluation, which is the value of the increased crop produced by the application of the fertilizer. It is evident that the agricultural value will vary with the soil, the crop, or the season, and may be above or below the total cost according to circumstances. In good fertilizer practice, the excess of the agricultural value over the total cost of the fertilizer, all costs incidental with the growing, harvesting, and marketing of the increase being first deducted, should be sufficient to give a handsome profit on the investment.

473. The buying of mixed goods. — The successful buying of mixed fertilizers on the retail market depends on two things: (1) the selection of a suitable composition, with carriers of known value; and (2) the purchase of high-grade goods. The farmer who observes these two points will have at least purchased successfully. Whether he obtains a profit from the use of the fertilizer depends on the balancing of a number of factors more or less variable from season to season.

The selection of a suitable fertilizer, as to carriers and composition for any particular crop or soil, entails first of all a study of the guarantee. Should the guarantee be such as that already cited, a large amount of information is at hand concerning the forms of the carriers and the availability of the important constituents. This knowledge, properly correlated with the probable needs of the crop and the soil, will determine whether that

particular brand should be purchased or not. The real question here is not the actual quantities of the elements in a ton of the fertilizer, but their balance among themselves. The actual pounds of nitrogen, phosphoric acid, or potash applied per acre can be governed by the rate at which the mixture is applied.

The purchase of high-grade goods is the second important point to be considered. Data collected from practically every state show that the higher the grade of the fertilizer, both as to availability and as to the percentage of the constituents carried, the greater is the amount of plant-food obtained for every dollar expended. The following data, taken from Vermont[1] for 1909, are the average of one hundred and thirty brands and are typical data in this regard:

Fertilizer	[illegible]	[illegible]	Excess over Commercial Valuation	Cost of Placing $1 [illegible]	Cost (in Cents) of One Pound of			[illegible]
					N	P_2O_5	K_2O	
								per cent
Low grade	$13.52	$27.10	$13.58	$1.00	.38	7.6	8.5	50.0
Medium grade	18.22	30.00	11.78	0.65	.31	6.3	7.0	60.6
High grade	26.30	38.93	12.63	0.48	.28	5.7	6.3	67.6

It is noticeable at once that the lower the grade of the fertilizer, the higher is the proportional cost of placing the goods on the market. In other words, it costs just

[1] Hills, J. L., Jones, C. H., and Miner, H. L. Commercial Fertilizers. Vermont Agr. Col., Bul. 143, pp. 147-149. 1909

as much per ton to market a low-grade material as a high-grade one. This accounts for the fact that the elements are cheaper per pound in a high-grade mixture, and that the value of plant-food received for every dollar expended is greater.

474. Home-mixing fertilizers. In comparing the above commercial evaluations with the prices actually paid by the farmer on the retail market, it is found that the latter shows an increase ranging from 48 to 100 per cent. This is due to the charges for mixing, transportation, handling, storage, commission, interest on capital, profit, and other items, made during the passage of the material from the wholesale dealer to the user. In order to escape these costs, many farmers have begun the practice of buying the separate carriers, thus avoiding these charges —except, of course, that of transportation. In many cases the mixing on the farm costs nothing, as it can be done in winter when the farm work is not pressing. Even if the farmer must charge himself with this mixing, it seldom amounts to more than fifty cents a ton.

As might be expected, this practice has met with much opposition from manufacturers. In general it is claimed that the factory goods are more finely ground than those mixed by the farmer, and consequently the ready-mixed goods are not only more uniform but also in better physical condition. Also, the manufacturer is able to treat certain materials with acids, and thus increase their availability. While these reasons are more or less valid, good results may be expected from a fertilizer even though it may not be quite uniform, as the soil tends to equalize this deficiency. Moreover, by screening and by using a proper filler, a farmer can obtain a physical condition which will in no way interfere with the drilling of the mix-

terial. While, obviously, one farmer alone cannot afford to buy direct from the wholesale dealer because of the high freight charges on small lots, this objection is being met by clubs and various organizations whereby the single carriers may be bought in carload lots.

It is evident that when a farmer mixes his own fertilizer he is able to obtain not only pure goods, but high-grade goods as well, thus reducing freight. Moreover, as a general thing home mixing is cheaper than buying the ready-mixed goods. A quotation from Connecticut[1] for 1906 illustrates about what this saving may be:—

PLANT-FOOD PURCHASED FOR $30

	Pounds N	Pounds P_2O_5	Pounds K_2O	Total
Nitrogenous superphosphates				
Best quality	73	188	111	372
Least valuable	23	279	53	355
Special manures				
Best quality	69	170	143	382
Lowest quality	33	174	66	273
Home mixtures				
Average of all	77	200	168	445

A third point, and by some considered to be more important than those already discussed, is the educational value of home mixing. No farmer can mix his own fertilizer without becoming familiar with the carriers, their availability, and their effects. He is forced to study their influence on the crops more closely, and thus is placed

[1] Jenkins, E. H., and Winton, A. L. Fertilizer Report. Conn. (New Haven) Agr. Expt. Sta., Rept. 1906, Part I, pp. 1-106.

in a position to make changes that will tend to a higher efficiency of the constituents. The chances are that he will alter his fertilizer mixture as his rotation progresses and his soil changes in fertility.

Such arguments do not always mean, however, that it pays to mix at home. As a matter of fact, in many cases it does not pay, especially where only a small amount of fertilizer is needed and it is impossible to coöperate with other farmers. As a general rule, fertilizers should be bought by the method that will give the greatest value for every dollar expended. Farmers often can avail themselves of the advantage of both systems by asking for bids from various manufacturers on carload lots of mixed goods having a certain designated composition. The farmers in this case designate the carriers as well. All the advantages of machinery mixing may thus be gained, with the lower cost which has made home mixing so popular.

475. Fertilizers not to be mixed. — Every farmer who practices home mixing should keep in mind that there are certain fertilizers which should not be mixed. This is due to the fact that a number of materials carry lime in the oxide, the hydrate, or the carbonate form. This lime, particularly the caustic forms, may react in three directions, depending on the fertilizer with which it is in contact: (1) in setting free ammonia, (2) in causing reversion of acid phosphate, and (3) in producing a bad physical condition, especially when in contact with materials more or less deliquescent. Van Slyke[1] may be quoted in this regard as follows: —

[1] Van Slyke, L. L. Fertilizers and Crops, pp. 485–486. New York, 1912.

1.	Calcium oxide Calcium hydrate Wood ashes Basic slag Calcium cyanamid Basic calcium nitrate	should not be mixed with	ammonium sulfate animal manures, as tankage, blood, and the like nitrogenous guanos
2.	Calcium oxide Calcium hydrate Calcium carbonate Wood ashes Basic calcium nitrates	should not be mixed with	soluble phosphates of any kind
3.	Calcium oxide Calcium hydrate Basic calcium nitrate	should not be mixed with (unless applied immediately)	sodium nitrate potassium chloride kainit, and the like

Neither is it wise to allow moist acid phosphate to be in contact with large quantities of sodium nitrate, as nitric acid may be slowly liberated by free sulfuric or phosphoric acid. Also, large quantities of calcium cyanamid should not be mixed with acid phosphate because of the lime contained in the former. If, however, the ratio is not greater than one to ten, the results are beneficial, since the reaction, without causing serious reversion of the phosphate, generates enough heat to quickly season the mixture. The fine and dry condition of the cyanamid is also conducive to a good mechanical condition, and accounts for the fact that this material is in such favor with manufacturers of mixed goods.

476. How to mix fertilizers. — As the various carriers are bought under guarantee, the percentages of nitrogen, phosphoric acid, and potash in the ingredients to be mixed are accurately known. The calculation of the amounts of each carrier and of the filler necessary to make up a ton of a fertilizer having a certain formula, then becomes a matter of simple arithmetic. The mixing is an equally simple operation. The implements needed in home mixing are as follows: (1) a tight floor, (2) platform scales, (3) a sand screen with from three to six meshes to an inch, (4) a tamper or a grinder, (5) shovels, a rake, and like tools.

First, the various ingredients, after being crushed and screened if lumpy, are weighed out in amounts sufficient for the unit of fertilizer to be mixed at any one time. The bulkiest material is spread on the floor first and leveled uniformly by raking. The remaining ingredients are then spread in thin layers above the first, in the order of their bulk. Beginning at one side, the material is next shoveled over, care being taken that the shovel reaches the bottom of the pile each time. The pile is then again leveled, and the process is repeated a sufficient number of times to insure thorough mixing. Sometimes a mixing machine may be used for this operation. For storage and general convenience, the fertilizer may be weighed into sacks of from 100 to 150 pounds capacity and put in a dry place until needed for use.

A word of caution should be inserted here regarding the concentration of the mixture. Some farmers, in order to lessen the work of mixing and application in the field, raise the percentage of the elements exceedingly high a condition very likely to occur when high grade materials are used. This is bad practice, in that it may interfere

with germination and may also injure the young plants. Also, it is likely to result not only in a poor physical condition but also in uneven distribution, which will bring about a lowered efficiency of the fertilizer. The use of sufficient dry, finely divided filler will obviate such dangers.

477. Factors affecting the efficiency of fertilizers. — The agricultural value of a fertilizer is necessarily a variable quantity, since, in applying fertilizers, a material subject to change is placed in contact with two wide variables, the soil and the crop. The general factors that govern the effect of fertilizers may be listed as follows:

1. *Seed, crop, and adaptation of crop to soil.* — It is quite evident that different crops will respond differently to the same fertilizer elements. Also, the strength of the seed, the management of the crop, and the adaptation of crop to soil, will be potent factors in variation.
2. *Temperature, sunshine, and rainfall.* — These factors are meteorological and, of course, are dominant in the growth of the plant. Rainfall especially is important, as an optimum moisture content is conducive to good plant development. In general, as shown by experiments in Ohio and Pennsylvania, the higher the rainfall, the greater is the efficiency of the fertilizer used.
3. *Drainage.* — This is of great importance in fertilizer practice, since it places the soil in a better condition from all standpoints for plant growth. In other words, the better the normal soil conditions, the better should be the reaction from fertilizer application.

4. *Physical condition of the soil.* — The addition of lime and organic matter, the utilization of drainage, tillage, and the like, all are conducive to higher crop returns through the indirect effect on fertilizer efficiency.
5. *Lime.* — Lime, by improving physical conditions, by setting plant-food free, by correcting acidity, by stimulating bacterial action, and by tending to eliminate toxic materials either directly or indirectly, is of great importance in fertilizer practice. In fact, certain fertilizers, such as ammonium sulfate and acid phosphate, do not reach their full efficiency unless plenty of lime is present.
6. *Organic matter.* — Besides the effect of organic matter on physical conditions and chemical reactions which indirectly influence fertilizer action, an important action is set up by organic matter in the encouragement of bacterial functions. As the favorable changes of fertilizers, especially those carrying nitrogen, is due to biological activity, the presence of organic materials becomes doubly important.
7. *Chemical composition of the soil.* — Since the full return from a fertilizer is derived when the elements are well balanced, the actual constitution of the soil becomes a factor, especially when ready availability is obtainable. Therefore, in choosing a fertilizer and deciding on the amounts to apply, the chemical condition of the soil is no mean factor.

While the conditions affecting fertilizer efficiency have thus been so briefly disposed of, it is evident that a more

detailed consideration of the question would be not only interesting but also profitable, would space permit. One point of broader scope, however, than the addition of a well-balanced food stimulation, stands out clearly in this consideration. The necessity of putting a soil in any given climate into the best possible condition for plant growth is paramount. This means that drainage, lime, humus, and tillage, in the order named, must be raised to their highest perfection. Under such improvements the further use of commercial fertilizers may or may not be a paying investment.

378. **Method and time of applying fertilizers.** — The distribution of the fertilizer by means of machinery is much more satisfactory than is broadcasting by hand, as the former method gives a more uniform distribution. Cereals and other crops are now usually planted with a drill or a planter provided with an attachment for dropping the fertilizer at the same time that the seed is sown, the fertilizer being by this method placed under the surface of the soil. Broadcasting machines are also used, which leave the fertilizer uniformly distributed on the surface of the ground, thus permitting it to be harrowed in sufficiently before the seed is planted, and preventing injury to the seed by the chemical activity of the fertilizing material.

Corn planters with fertilizer attachments deposit the fertilizer beneath the seed, thus avoiding a possible detrimental contact. Grain drills do not do this, and, where the amount of fertilizer used exceeds 300 or 400 pounds an acre, it is better to apply it before seeding. Grass and other small seeds should be planted only after the fertilizer has been mixed with the soil for several days. For crops to which large quantities of fertilizers

are to be added, especially potatoes and garden crops, it is desirable to drop only a portion of the fertilizer with the seed, the remainder having been broadcasted by machinery and harrowed in earlier.

479. **Fertilizing crops.** — Three primary considerations must be observed in the actual utilization of fertilizers: (1) the percentage of nitrogen, phosphorus, and potash suited to the crop and the soil; (2) the availability of the carriers; and (3) the amounts to be applied. It is evident, due to so many factors that are difficult to control, that fertilizer formulas for different crops on particular soils are difficult to determine. In fact, such data can never be more than merely suggestive. Further, the best quantity of a mixture to apply, even though it is perfectly balanced, is a figure that can only be approximated. Probably the largest percentage of the fertilizer waste that occurs annually can be charged to this factor. Many farmers make the mistake of applying too much fertilizer. As a consequence, any information along such lines can only be merely suggestive, rather than literal, it being understood that the general formulas suitable to various crops, and the quantities ordinarily applied, are subject to wide variations.

The fact that there are so many mixtures on the market in this country for the same crops would be rather amusing, did it not so strikingly expose the ignorance of the manufacturer as well as the gullibility of the public. Recognizing the need of standard formulas subject to change according to local conditions, Van Slyke[1] has offered the following for general use:

[1] Van Slyke, L. L. Fertilizers and Crops, p. 528. New York. 1912.

FERTILIZER FORMULAS FOR GENERAL APPLICATION

Crops	Percentage of N	Percentage of P_2O_5	Percentage of K_2O
Leguminous	1	8	10
Cereal	3	8	5
Garden	4	8	10
Grass	3	6	9
Orchard	2	5	10
Root	3	8	7

While it is recognized that these formulas are probably far from correct in their application to such groups as the garden crops, where so many entirely different plants are concerned, it is felt that they furnish the basis, as far as our knowledge now extends, for a more economic fertilization. The variation of such mixtures to suit specific needs is a part of fertilizer practice.

The carriers largely used for such readily available mixtures are sodium nitrate, acid phosphate, and potassium chloride or sulfate. Tankage or blood is often substituted for sodium nitrate where humus is desirable, while ammonium sulfate and calcium cyanamid are growing in popularity. Raw rock phosphate and basic slag are used rather largely in separate applications, the amounts being usually larger than with the ordinary fertilizer materials.

The other phase of fertilizer practice is in the amount to be applied. With all the groups considered above except garden and root crops, the applications are relatively light, ranging from 150 to 300 pounds to an acre. Where excessive vegetative growth is required, as in silage, the rate may be increased to 500 pounds. In the top dressings of meadows or grains, the rate varies from 75

to 150 pounds an acre. Very often this dressing is sodium nitrate alone. With garden and root crops the amount of fertilizer applied is very large, ranging from 800 to sometimes as high as 2000 pounds. The cropping here is intensive, and the expenditure for fertilization may be large and yet yield handsome profits.

It must always be remembered that in fertilizer practice the very high yields obtained under fertilizer stimulation are not always the ones that give the best returns on the money invested. In other words, the law of diminishing returns is a factor in the influence of fertilization on crop yield. This relationship is clearly shown by the curve illustrating the law of the minimum (par. 460), in which the return for each increment of fertilizer becomes less and less as the *total quantity* added becomes greater. It is evident, therefore, that with an excessive application of any mixture, the returns to an increment will at last become so small that the increased crop fails entirely to pay for even the fertilizer, not to mention such charges as cost of application, harvesting of increased crop, storage, and the like. The application of moderate amounts of fertilizer is to be urged for all soils until the maximum paying dose that may be applied to any given crop is ascertained by careful experimentation. Over-fertilization probably accounts for the fact that such a large proportion of the fertilizers sold to the farmers each year not only is entirely wasted, but probably in some cases even becomes detrimental to crop yield.

480. **Systems of fertilization.** — During the evolution of fertilizer practice, particularly since the early part of the nineteenth century, a number of systems of applying fertilizer have been advocated or have been in actual use. These may be listed as follows: —

1. *Single-element system.* — This was one of the first to be suggested, and was advocated because each particular crop was supposed at that time to respond largely to one element. Thus, nitrogen was supposed to dominate wheat, rye, and oats; phosphoric acid, to dominate corn, turnips, and sorghum; and potash to dominate potatoes, clover, and beans. Present knowledge of the balancing effects of fertilizers shows this idea to be fallacious.
2. *Abundant supply of minerals.* — This system had its origin from the fact that potash and phosphoric acid are relatively cheap and are slowly leached from the soil, while nitrogen is expensive and easily lost. Such a plan, therefore, provides always plenty of potash and phosphorus, which is to be balanced each season with sufficient nitrogen to give paying yields.
3. *A system based on the plant-food taken out by the crop.* — According to this plan, as much plant-food is added each year as will probably be taken out by the plant, this being determined by chemical analyses. This system overlooks the fact not only that different plants feed differently on the same soil, but that the same crop exhibits marked variability with change of season and change of soil. Moreover, no allowance is made for losses by leaching, which are known to equal at times the losses due to plant growth.
4. *Irrational system.* — This is the plan followed by many farmers where fertilizers are an important factor in soil management. The formula is changed from year to year, in a vain attempt to strike a

high point in production. The same continual shift is found in the quantities applied. Too often the specific brand used is determined by the trade name that it carries or by the recommendation of the retail merchant, rather than from a careful consideration of the guarantee or of the carriers for each important element. The educational phase of home mixing should do much to eliminate this system.

5. *Fertilization of the money crop.*— In trucking or in general farming operations one crop is usually a money crop. Naturally its stimulation by heavy fertilization will pay better than applications to crops that bring less on the market. The general plan in this system is to allow the crops following the money crop to utilize the residuum. When this residual influence works out, the system is likely to be a profitable one, but when the following crops fail to respond, the method becomes wasteful in the extreme.

In the selection of a system that will result in an effective utilization of fertilizers, only two of the plans described above need be considered. In any fertilizer, phosphoric acid and potash should always be present in amounts sufficient to more than balance the nitrogen, since the activity of nitrogen is so pronounced. Therefore a scheme that calls for an abundance of minerals is a sound one. This, coupled with the heavy fertilization of the money crop, does not, however, constitute what might be considered a rational system, since the crops that follow may or may not be adequately supplied with plant-food. Uneven fertilization often leaves the soil,

as far as its balance is concerned, less able to yield a paying crop than before. The careful fertilization of the rotation, then, with special attention to the money crop, is the only rational system that can ordinarily be employed, since it not only cares for the crop on the land but also looks to those that are to succeed. The attention that must necessarily be paid to the fertility of the soil in such a system insures the establishment of a soil management which will ultimately result in a great conservation of fertility, while at the same time raising the yields and increasing the prosperity of the farming class.

CHAPTER XXVI

FARM MANURES

Of all the by-products of the farm, barnyard manure is probably the most important, since it affords a means whereby the unused portion of the crop, the residue of the finished farm product, may again be returned to the soil. This country is now entering on an era in which the prevention of all waste is becoming more and more necessary and a nearer approach to a self-sustaining system of agriculture far more essential. A clear understanding of the composition of farm manure, the changes it undergoes, and its avenues of loss, and also of methods for its practical handling, and a realization of its effects both on soil and on crop, are of vital importance. This need appeals not only to the practical man but to the theoretical and technical man as well, for here is a field in which theory and practice not only meet but widely overlap.

481. General character and function of farm manures. — The term farm manure may be employed in reference to the refuse from all animals of the farm, although, as a general rule, the bulk of the ordinary manure which ultimately finds its way back to the land is produced by cattle and horses. This arises not only because these animals consume the greater part of the grain and roughage on the average farm, but also because the methods of handling them make it easier and more practicable to

conserve their excreta. Yard manure generally refers to mixed manures. The mixing usually occurs during storage, either for convenience in handling or for the purpose of checking losses and facilitating fermentation. Thus, horse and cow manures are commonly mixed, since the too rapid fermentation and probable loss of ammonia in the former is checked, while at the same time a more rapid and much more complete decay is encouraged in the latter.

The ordinary manure consists of two original components, the solid and the liquid portion. As these constituents differ greatly, not only in composition but also in physical properties, their proportions must appreciably affect the quality of the excreta and its agricultural value. Litter added for bedding or for adsorptive purposes is almost always an important factor, for while it prevents losses of the soluble constituents it may at the same time lower the value of the product for a unit amount.

Farm manure ordinarily fulfills two functions which are usually not so simultaneously yet clearly developed in any other material — that of a direct and that of an indirect fertiliser. Consisting of 73 per cent of water and only 27 per cent of dry matter, the percentages of plant-food are necessarily low. As mixed farm manure contains on the average[1] 0.50 per cent of nitrogen, 0.25 per cent of phosphoric acid, and 0.60 per cent of potash, considerable quantities of plant-food elements are added in an ordinary application. Ten tons of average manure, even if only one-half of the nitrogen, one-sixth of the phosphorus, and one-half of the potash are readily available, is equivalent to 330 pounds of sodium nitrate, 60

[1] See Analyses, Storer, F. H. Agriculture, pp. 237-248. New York. 1910.

pounds of acid phosphate, and 125 pounds of potassium chloride. This is equivalent to the addition of 486 pounds of an approximately 10-2-12 ready-mixed fertilizer. Moreover, from the fact that so large an amount of the plant-food carried is not readily available, it acts as a residuum, which is slowly given up to the succeeding crops. It has been shown in England[1] that paying increased returns may be obtained from manure four years after its application. At Rothamsted, England,[2] a residual impetus was noticeable on crops forty years after the soil was manured. This, however, is an exceptional case.

Farm manure may act as an indirect fertilizer in its tendency toward improved physical relations. The addition of organic matter is the vital factor here. Better tilth, better aeration, improved drainage, and increased water capacity are the necessary accessories to a rise in humus content. The influence of manure on the availability of the mineral constituents of the soil is not the least of its indirect effects. Even the increased absorptive power of the soil should be mentioned, in its tendency toward the counteraction of toxic principles.

Another general characteristic of average farm manure is that, while it is a fertilizer, it is an unbalanced one. Proportioned very roughly to a 10-2-12 commercial mixture, any one acquainted with general fertilizer practice can see that it is too high in nitrogen and too low in available phosphoric acid. The elimination of such a condi-

[1] Voelcker, J. A., and Hall, A. D. The Valuation of Unexhausted Manures Obtained by the Consumption of Foods by Stock. London. 1908.

[2] Hall, A. D. Fertilizers and Manures, p. 312. New York, 1910.

tion and a balancing thereby of the plant ration is one of the many problems that present themselves in the economic handling and utilization of animal residues.

492. Variable composition of manures. — The manure produced on an average farm is rather likely to vary markedly in composition and character from time to time. It may even change radically from one day to another. There are five general factors that are usually listed as being responsible for this variation: (1) litter; (2) class of animal; (3) individuality, condition, and age of animal; (4) food of animal; and (5) handling of manure.

493. Litter. Perhaps under ordinary circumstances the amount and character of the litter has as much to do with the variation in manurial composition as has any other one factor, if not more. By an increase in the amount of bedding, the product becomes bulky, light in weight, and difficult to handle. This is likely to be the case with manure from livery stables, where the litter is used to keep the horses clean and not for purposes of plant-food conservation. That bedding must also exert a marked effect on chemical composition is evident from the following analyses: —

COMPOSITION OF LITTER

	N	P_2O_5	K_2O
Sawdust shavings	0.40	0.20	0.40
Oat straw	0.62	0.20	1.04
Peat	2.03	0.20	0.17
Leaves	0.65	0.15	0.30

Sawdust and shavings add little of value to the manure and really act as a diluent. While they are good absorb-

cuts they decompose so slowly as to make them somewhat objectionable on light soils. Leaves decompose readily, but add little fertility. Oat straw carries no more nitrogen than does average manure, and this nitrogen, like that of peat or muck, is not readily available as plant-food. Litter, however, is of such extreme importance as an absorbent that the resistant qualities of even such materials as shavings can be to a degree ignored. Because of the influence of the bedding on composition, manure should never be bought unless this phase has been carefully looked into.

484. Class of animal. — The second factor causing radical variation in the composition of farm manure is the class of animal by which it is produced. The following figures,[1] compiled from Ohio, Connecticut, and New York (at Cornell University), illustrate this point clearly: —

	Percentage of			
	H_2O	N	P	K
Horse manure with straw	62.80	0.67	0.12	0.54
Cow manure with straw	78.00	0.46	0.13	0.36

A working horse on maintenance ration will return in the manure almost all the nitrogen and minerals taken as food. In other words, the building-up and the breaking-down, or elimination, processes are about equal. A young fattening pig, on the other hand, will return only about 85 per cent of the nitrogen received as food and 96 per cent of the mineral material, and a milking cow 75 per cent and 89 per cent, respectively.

[1] Thorne, C. E. Farm Manures, p. 89. New York. 1914.

485. Individuality, condition, and age of animal. — Various animals differ in capacity, some retaining much more of the elements contained in the food than do others, and consequently producing a poorer manure. The service to which the animal is subjected is also a factor. A milch cow will certainly utilise more nutriments than an animal not in that condition. Age is perhaps more accountable for variation in farm manure than either of the other two causes. A young animal gaining in muscle and bone is storing away large quantities of nitrogen, phosphorus, and potash, and producing a manure correspondingly poorer in these ingredients.

486. Food of animal. — Since the animal will retain only a certain quantity of the food elements, it is reasonable to suppose that the richer the food, the richer will be the corresponding excrement, both liquid and solid. Such has proved to be the case. Wheeler,[1] in studying the rations of chickens, found the following difference in the manure produced: —

Ration	Percentage of			
	H_2O	N	P	K
Fresh hen manure (nitrogenous ration) . . .	59.7	0.90	0.41	0.37
Fresh hen manure (carbonaceous ration) . .	55.3	0.66	0.32	0.31

From Ohio,[2] where the production of manure has been most thoroughly investigated, the following data may be quoted: —

[1] Wheeler, W. P. Poultry Feeding Experiments. Rept. New York (Geneva) Agr. Exp. Sta., No. 8, p. 62. 1889.

[2] Thorne, C. E., and others. The Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183. 1907.

EFFECT OF RATION ON MANURIAL COMPOSITION

RATION	PERCENTAGE OF		
	N	P	K
Corn and mixed hay	1.49	0.28	1.01
Corn, oil meal, and hay	1.55	0.24	1.02
Corn, oil meal, and clover	1.68	0.26	1.04

487. **Handling manure.** — In dealing with a product of which almost one-half is liquid, there is great danger that a considerable amount of valuable plant-food will be lost by leaching. The modification and consequent lowering of the plant-food value of farm manure is a vital question in the economic handling of this product. Next to the litter, lack of care is perhaps the most important single factor concerned in altering the chemical composition of manures in general. The influence of handling is so clearly brought out by the following figures from Shutt,[1] on mixed horse and cow manure, that further discussion seems unnecessary. The protected manure in this case was in a bin under a shed. The exposed sample was in a similar bin but unprotected from the weather:

	LOSS IN BIN AT SIX MONTHS (PERCENTAGE)		LOSS IN BIN AT TWELVE MONTHS (PERCENTAGE)	
	Protected	Exposed	Protected	Exposed
Loss of organic matter	58	65	60	69
Loss of nitrogen	19	30	23	40
Loss of phosphoric acid	0	13	4	16
Loss of potash	3	20	3	35

[1] Shutt, M. A. Barnyard Manure. Canadian Dept. Agr., Cent. Exp. Farm, Bul. 31. 1898.

288. Composition and character of farm manures. — Although the probable composition of farm manures is so difficult to state in exact figures, compilations of the available data have yielded percentages which, while they demand a most liberal interpretation, afford considerable light regarding the differences that normally exist between the excrement of various animals. Of these compilations, Van Slyke's is perhaps the best.

THE COMPOSITION OF FRESH MANURES[1]

Excrement		Percentage of			
		H_2O	N	P_2O_5	K_2O
Horse	Solid 80 per cent	75	0.55	0.30	0.40
	Liquid 20 per cent	90	1.35	Trace	1.25
	Whole manure	78	0.70	0.25	0.55
Cow	Solid 70 per cent	85	0.40	0.20	0.10
	Liquid 30 per cent	92	1.00	Trace	1.35
	Whole manure	86	0.60	0.15	0.45
Sheep	Solid 67 per cent	60	0.75	0.50	0.45
	Liquid 33 per cent	85	1.35	0.05	2.10
	Whole manure	68	0.95	0.35	1.00
Swine	Solid 60 per cent	80	0.55	0.50	0.40
	Liquid 40 per cent	97	0.40	0.10	0.45
	Whole manure	87	0.50	0.35	0.40

Since the horse does not ruminate its food, the manure is likely to be of an open character. It is also a fairly dry manure, as is that from sheep, the liquid in these two manures making up 20 and 33 per cent, respectively, of the whole product. The complete manure from these two animals contains 78 and 68 per cent, respectively,

[1] Van Slyke, L. L. Fertilizers and Crops, p. 391. New York. 1912.

of water — a considerable contrast to the 86 and 87 per cent presented by the cattle and swine excrements. Cattle and swine manures, being very wet, are rather solid and compact. The air, therefore, is likely to be excluded to a large degree and decomposition is relatively slow. They are usually spoken of as cold, inert manures as compared with the dry, open, rapidly heating excrements obtained from the horse and the sheep.

In every case except that of swine the liquid portion of the various excrements is much the richer in nitrogen, containing on the average more than twice as much when compared on the percentage basis. The liquid is also richer in potash than the solid, averaging for the four classes of animals 1.36 per cent as compared to 0.34 per cent contained in the solid manure. Most of the phosphoric acid, however, is contained in the solid excrement, only traces being found in the urine except in the case of the swine. It is therefore evident that the liquid manure, pound for pound, is more valuable in so far as the plant-food elements are concerned. The advantage leans heavily toward the urine also in that the constituents therein contained are immediately available; this cannot be said of the solid manure.

409. Actual plant-food in liquid and solid excrement. — While the liquid manure carries more nutriments to an equal weight than the solid, it yet remains to be seen which actually carries more of the primary food elements. In general, more solid manure is excreted than liquid, tending to throw the advantage toward the former in so far as total food elements are concerned. The following table, adopted from Van Slyke,[1] bears on this point:

[1] Van Slyke, L. L. Fertilizers and Crops, p. 285. New York. 1912.

DISTRIBUTION OF PLANT-FOOD CONSTITUENTS BETWEEN THE LIQUID AND THE SOLID OF WHOLE MANURE

Excrement	Percentage of Total Nitrogen		Percentage of Total Phosphoric Acid		Percentage of Total Potash	
	Solid	Liquid	Solid	Liquid	Solid	Liquid
Horse	62	38	100	0	56	44
Cow	49	51	100	0	16	84
Sheep	52	48	95	5	30	70
Swine	67	33	88	12	57	43
Average	57	43	95	5	40	60
Average for horse and cow	56	45	100	0	35	65

It is seen here that a little more than one-half the nitrogen, almost all the phosphoric acid, and about two-fifths of the potash, are found in the solid manure. Nevertheless this apparent advantage of the solid manure is balanced by the ready availability of the constituents carried by the urine, giving it in total about an equal commercial and agricultural value with the solid excrement. Such figures are suggestive of the care that should be taken of the liquid manure. Its ready loss of nitrogen by fermentation, and the ease with which all its valuable constituents may escape by leaching, should make it an object of especial regard in handling.

490. Production of manure. — A well-fed, moderately worked horse will produce daily from 45 to 55 pounds of manure, of which from 10 to 11 pounds is urine. A cow, on the other hand, having a greater food capacity, will excrete from 70 to 90 pounds during the same period, of which from 20 to 30 pounds is liquid. Swine and

sheep, varying so greatly in weight, will excrete such widely different quantities that it is difficult and misleading to express the amount based on the individual. A clearer method of comparison is that employed below, in which a thousand pounds in weight of animal is made the basis of the calculation:—

MANURE EXCRETED BY VARIOUS FARM ANIMALS TO THE 1000 POUNDS LIVE WEIGHT

Animal	Pounds a Day	Tons a Year
Horse [1]	50	9.1
Cow [2]	70	12.7
Steer [3]	40	7.3
Swine [4]	85	15.5
Sheep [5]	34	6.2

It is quite evident that, for the weight of animal, the swine and the cow give the heaviest production of manure on the farm, but it should be remembered also that they consume the greatest amount of food. Whether these animals are the most economical in production of manure must depend largely on age and individuality.

[1] Roberts, I. P., and Wing, H. H. On the Determination of Farmyard Manure by Feeding and Fermentation. Cornell Univ. Agr. Exp. Sta., Bul. 13. 1889. Also, Roberts, I. P. The Production and Care of Farm Manure. Cornell Univ. Agr. Exp. Sta., Bul. 27. 1891. Also, Watson, G. C. The Production of Manure. Cornell Univ. Agr. Exp. Sta., Bul. 56. 1893.

[2] Thorne, C. E. Farm Manures, p. 97. New York. 1914.

[3] Thorne, C. E., and others. The Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183. 1907.

[4] Watson, G. C. The Production of Manure. Cornell Univ. Agr. Exp. Sta., Bul. 56. 1893.

[5] Van Slyke, L. L. Fertilizers and Crops, p. 294. New York. 1912.

491. **Heiden's formulas.** — Perhaps a better and more nearly accurate means of calculating the probable production of manure is from the food consumed, rather than from the combined weight of animals kept. Formulas have been devised from experimental data in Germany and are designated as Heiden's formulas.[1] From the amount of absolute dry matter fed and the excrement produced, Heiden was able to determine certain definite relationships of the latter to the former. These, of course, varied for different animals, being 2.10 for the horse, 3.80 for the cow, and 1.80 for sheep. For example, if a horse received 20 pounds of dry matter daily, the manurial production would be 42 pounds. Such formulas are of particular value on English farms, where the incoming renter must pay the preceding tenant for the manure produced on the farm during previous years.

492. **Poultry manure.** — The excrement from poultry is extremely variable, due to causes that have already been discussed. In general, this manure is much richer than that from other farm animals. Storer[2] cites the following analysis: —

Composition of Poultry Manure

	Per cent
Water	0.56
Nitrogen	1.60
Phosphoric acid	1.75
Potash	0.90
Lime	2.25

[1] Henry, W. A. Feeds and Feeding, p. 365. Madison, Wisconsin. 1904.

[2] Storer, F. H. Agriculture, Vol. I, p. 443. New York. 1910. Also, Voorhees, E. B. Ground Bone and Miscellaneous Samples. New Jersey Agr. Exp. Sta., Bul. 84. 1891. Also,

It is evident that poultry excrement is the most valuable manure produced on the farm. It dries readily and the loss of nitrogen by fermentation is not great. Because of its great strength farmers are very careful regarding its application, as injurious effects on the crop may result. Notwithstanding its great value it probably receives less care than any other manure produced on the farm.

493. Commercial and agricultural evaluation of manures. — For purposes of comparison, experimentation, and sale, farm manures are often evaluated in a way similar to that used with commercial fertilizers. The great difficulty here lies in arriving at prices for the important constituents which are at all comparable with the value of the manure in the field. The following figures are calculated from the preceding tables, and show not only the comparative value of the fresh excrement from different sources but also what might be considered as fair prices a ton for the manures. The value of the nitrogen is here placed at ten cents a pound, the phosphoric acid at two and one-half cents, and the potash at four cents: —

	Value of manure a ton
Swine manure	$1.50
Cow manure	1.64
Horse manure	1.97
Sheep manure	2.87
Poultry manure	4.80
Average of cow manure and horse manure mixed	1.80

Goessmann, C. A. Massachusetts State Exp. Sta., Bul. 37, 1890, and Bul. 63, 1896.

This commercial evaluation, of course, must be applied with care because of the many factors tending to vary the composition of the excrement. Litter, particularly, will exert a great influence in this direction. Perhaps a safe figure as regards the commercial value of manure as it is likely to be handled on the average farm is about $1.50 a ton. This approaches more nearly the price that a market gardener, for example, may pay for such a product.

This commercial evaluation must never become confused with what is known as the agricultural value of a manure. The former is based on composition, while the latter arises from the effects as measured in crop growth. A manure of high commercial value may, when placed on the soil, yield only a low to medium agricultural return. This latter evaluation is, of course, the one of greatest significance in agricultural practice. A very good example of this might be cited from the Ohio experiments[1] with manure. In this case both treated and untreated manures were evaluated commercially and were then applied to the land. The value of the increased crops in a three-years' rotation was then calculated in terms of return to a ton of manure applied: —

COMMERCIAL AND AGRICULTURAL EVALUATION OF MANURES

MANURE	COMMERCIAL VALUE	AGRICULTURAL VALUE
Yard manure untreated	$1.41	$2.15
Yard manure plus floats	2.04	3.31
Yard manure plus acid phosphate	1.65	3.07
Yard manure plus kainit	1.45	2.79
Yard manure plus gypsum	1.48	2.76

[1] Thorne, C. E., and others. The Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183, pp. 209–219. 1907.

In practice, then, it is this agricultural evaluation which must be especially watched. Its expression should be not only in net yield to the acre, but also in net return to a ton of manure applied.

494. **The fermentation of manure.**[1]—During the processes of digestion the food of animals becomes more or less decomposed and decayed. This condition comes about partly because of the digestive processes and partly from the bacterial action that takes place, largely in the lower intestines. Of these two influences within the animal, bacterial activities are probably of the greater importance as far as the breaking up of the complicated foodstuffs is concerned. The fresh excrement, then, as it comes from the stable, consists of decayed or partially decayed plant materials, with a certain amount of broken-down animal tissue and mucus. This is more or less intimately mixed with litter and the whole mass is wetted, or moistened, with the liquid excrement, carrying, as it does, considerable quantities of soluble nitrogen and potash. This mass of material, ranging from the most complex compounds to the most simple, is teeming with bacteria, especially those that function in decay and putrefaction. The number very often runs into billions to a gram of excrement. In such an environment it is of little wonder that biological changes go on so rapidly.

Although so many different groups of organisms live and function in manure, and although so many products, both simple and complex, are continually being split off, for convenience and simplicity the bacteria may be

[1] Good discussions may be found as follows: Lipman, J. G., Bacteria in Relation to Country Life, pp. 308-356. New York. 1911. Hall, A. D., Manures and Fertilizers, pp. 184-216. New York. 1910.

grouped under two heads, aërobic and anaërobic. The former work in the presence of oxygen, the latter when air is either lacking or only very slightly present. This grouping is not a distinct one by any means, as many organisms may function not only in air but also when oxygen is lacking. The products, however, are as different under these two conditions as if they arose from distinct organisms.

495. Aërobic action. — When manure is first produced it is likely to be rather loose, and if allowed to dry at once it becomes well aërated. The first bacterial action is therefore likely to be rather largely aërobic in nature. Transformations are very rapid and are accompanied by considerable heat, ranging from 100° to 130° F. and sometimes higher. This action falls largely on the simple nitrogenous compounds. Urea is principally affected, and will very quickly disappear from well-aërated manure. The reaction is as follows: —

$$CON_2H_4 + 2\,H_2O = (NH_4)_2\,CO_3$$

The ammonium carbonate is a volatile compound, and on the least exposure and evaporation of the manurial liquids it changes into ammonia and carbon dioxide. Thus nitrogen may be rapidly lost from manure by the unwise allowing of excessive aërobic decay and decomposition to proceed.

This complex group of aërobic putrefactive organisms also attack to a certain extent the more complicated nitrogenous compounds, as well as some of the simpler carbohydrates contained in the solid and the liquid portions of the manure. More carbon dioxide therefore results, as well as certain simplified products which ultimately may be reduced to such a form as to be available as plant-

food. In other words, the whole mass of the manure tends to simpler forms. The mass becomes decayed, humus is produced, and available plant-food is evolved.

496. **Anaërobic action.** As the manure becomes compacted, especially if it is left moist, oxygen is gradually excluded within the heap and its place is taken by carbon dioxide, which is given off during the process of any form of bacterial activity. The fermentation now changes from aërobic to anaërobic, it becomes slower, and the temperature falls to as low as 80° or 90° F. New organisms may now function, and even some of the same ones that were active under aërobic conditions may continue to be effective. The process is now a deep-seated one and the products become changed to a considerable degree. Carbon dioxide, of course, continues to be evolved, but instead of ammonia being formed the nitrogenous matter is converted into the usual putrefactive products, such as indol, skatol, and the like. The carbonaceous matter is resolved into numerous hydrocarbons, of which methane (CH_4) is prominent; and as a by-product of the breaking-down of the proteins, hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) are evolved. The complex nitrogenous and carbohydrate bodies are attacked with the splitting-off, not only of simpler materials, but often of those more complex. Such compounds may be listed in general as organic acids and humic bodies. They of course ultimately succumb to simplification.

497. **Fermentation in general.** In any process of fermentation, acids tend to form which if not neutralized will render the mass acid and impede bacterial activity. This occurs when the solid excrement decomposes alone. The liquid manure, however, is alkaline and will tend to correct any acidity due to fermentation. The advan-

tage of either handling the liquid and the solid together, or pumping the liquid over the solid at intervals, is therefore apparent.

The general changes in any manure pile can readily be recapitulated. First is the aërobic action, with escape of ammonia and carbon dioxide. Next the manure is wetted, it compacts, and the slow, deep-seated decay sets in with a simplification of some compounds, with the production of acids, and with a gradual formation of humic materials. As the manure becomes alternately wet and dry, the two general processes may follow each other in rapid succession, the anaërobic bacteria attacking the complex materials, the aërobic affecting both the complex and the simpler compounds. Carbon dioxide is given off continuously during the process.

398. Gases from manure. — The changes in the composition of the gases drawn from wet and compact manure, as compared with those from the same pile dry and open, are well shown from results by Dehérain.[1] The pile in this experiment was about eight feet high: —

Composition of Gases from Dry and Moist Manure

Manure		Percentage of			
		CO_2	O_2	CH_4	N
Dry manure	Top	7.2	7.0	0.0	85.8
	Middle	14.5	4.7	1.3	79.6
	Bottom	50.8	0.0	49.2	0.0
Wet and compact manure	Top	42.7	1.1	52.4	3.8
	Middle	48.8	0.0	48.3	2.9
	Bottom	47.8	0.0	51.2	1.0

[1] Hall, A. D. Fertilizers and Manures, p. 168. New York. 1910.

It is noticeable that nitrogen ceases to be lost under anaërobic conditions, but the production of methane is much increased. Carbon dioxide is present at all times.

493. **Change of bulk and composition of rotting manure.** — Because of the great loss of carbon dioxide during the fermentation processes, there is a considerable change in bulk of the manure. Fresh excrement loses 20 per cent in bulk by partial rotting, 40 per cent by more thorough rotting, and 60 per cent by becoming completely decomposed. This means that 1000 pounds of fresh manure may be reduced to 800, 600, or 400 pounds, according to the degree of change it has undergone.

Although considerable loss of nitrogen may have occurred through aërobic bacterial action, and although both nitrogen and the minerals may have been considerably leached away, the loss of carbon dioxide is so much greater that generally there is an actual percentage increase of the former constituents in the well-rotted product. This relationship is well shown by figures from Wolff,[1] in which the samples were compared on the basis of equal amounts of dry matter:

Composition of Fresh and Decomposed Manure

	Fresh (Per cent)	Rotted (Per cent)
Ash	3.81	4.78
Nitrogen	0.39	0.40
Potash	0.45	0.58
Lime	0.48	0.61
Magnesia	0.13	0.15
Phosphoric acid	0.18	0.23
Sulfuric acid	0.10	0.13

[1] Aikman, C. M. Manures and Manuring, p. 288. Edinburgh and London. 1910.

It must be remembered, however, that this is only a general case and holds good only when the manure has had fairly careful attention. When the manure has been improperly handled, the soluble constituents may be lost as soon as formed and a rotted product may result which is very low in nitrogen, potassium, and phosphorus. It is therefore evident that the handling of the fresh manure is a controlling factor in the ultimate value of the product.

A further insight into the condition of rotted manure is given by Voelcker,[1] the data being calculated to a dry-weight basis: —

	Fresh Manure (Per cent)	Rotted Manure (Per cent)
Soluble organic matter	7.33	16.03
Soluble inorganic matter	4.55	5.98
Insoluble organic matter	78.14	51.34
Insoluble inorganic matter	11.98	27.50

These figures show the increased soluble matter in well decomposed manure and emphasize the value of rotting. The great loss of organic matter through the giving-off of carbon dioxide is also evident.

600. Fire-fanging of manure. — A change of a fermentative nature which sometimes takes place in loose and well-dried manure is fire-fanging. Many farmers consider this to be due to actual combustion, as the manure is very light in weight and has every appearance of being burned. This condition, however, is produced by fungi instead of bacteria, and the dry and dusty appearance of the

[1] Halligan, J. E. Soil Fertility and Fertilizers, p. 67. Easton, Pennsylvania. 1912.

manure is due to the mycelium, which penetrates in all directions and uses up the valuable constituents. Manure thus affected is of little value either as plant-food or as a soil amendment.

605. Waste of farm manures. — Any system of agriculture, in order to be permanent, must arrange for the addition of as much plant-food as is removed in the crop and the drainage water combined. Even if all of the crop were returned to the soil, a permanent system of agriculture would fall far short of being established, since at least as much plant-food is removed by leaching as by cropping. As a matter of fact, it is not even possible to return to the land as farm manure all the constituents taken off in the crop, due to the ease with which loss occurs. These losses may be grouped under two general heads: (1) those that occur as the food passes through the animal; and (2) those that are due to leaching and fermentation.

606. Losses due to digestion. — A certain quantity of material is necessarily taken from the original food as it passes through the animal. This loss falls most heavily on the organic matter and only slightly on the mineral constituents. Wolff[1] presents the following figures averaged from all classes of animals.—

PERCENTAGE OF ORIGINAL FOOD CONSTITUENTS RECOVERED IN FRESH MANURE

	Solid Manure	Liquid Manure	Total
Organic matter . . .	42.5	3.4	45.9
Nitrogen	50.1	47.2	97.3
Minerals	58.7	39.0	97.7

[1] Aikman, C. M. Manures and Manuring, pp. 228 and 233. Edinburgh and London. 1910.

It is to be noted that the organic matter of the food has sustained an average loss of about 55 per cent, while the loss of nitrogen and of minerals has been 18 per cent and 2 per cent, respectively. The loss of the organic matter is especially serious, although it can be replaced by using green manures and the practicing of a proper rotation. The loss of nitrogen can be replaced only by the growing of legumes or by the addition of a nitrogenous fertilizer.

503. Losses due to leaching and fermentation. — As about one-half of the nitrogen and two-thirds of the potash in farm manures is in a soluble condition, the possibility of loss by leaching is very great, especially where the manure is exposed to heavy rainfall. The loss of phosphorus is also of some consequence. In addition, the fermentation, especially that of an aerobic nature, will cause the formation of ammonia, which may be lost in large quantities if steps are not taken to control such action. It is evident that losses by leaching may be checked considerably by protecting the manures from excessive rainfall and by providing tight floors in the stable or an impervious bottom in the manure pit or under the manure pile. Packing and moistening the manure will change the aërobic fermentation to anaërobic, thus reducing very markedly the production of ammonia while allowing a simplification of the manurial compounds to proceed steadily. All wise methods of handling and storing manures provide against these losses through leaching and fermentation by protecting the manure from rain and by controlling fermentation through moistening and compacting.

It is very difficult, in quoting figures for waste of manure, to separate the losses due to leaching from those due to fermentation. The two processes go on simul-

taneously, and the loss from one source is dependent, to a certain extent, on the other. It is only the nitrogen, however, that may be lost by both fermentation and leaching, the minerals being wasted only through the latter avenue. A few figures regarding the losses to manures when exposed to atmospheric conditions may not be amiss at this point:—

LOSSES FROM MANURE THROUGH LEACHING AND FERMENTATION

	New York[1]	New York[1]	Canada[2]	New York[3]	New Jersey (Average for eight years)	Ohio[4]
Kind of Manure	Horse	Horse	Horse	Cow	Cow	Steer
Time exposed (days) .	183	183	274	180	77	91
Loss of nitrogen (percentage)	30	60	49	41	31	30
Loss of phosphoric acid (percentage) . . .	50	42	36	19	19	23
Loss of potash (percentage)	60	76	34	8	48	58

It seems evident that when manure is exposed to atmospheric agencies, even under the best conditions, the losses of nitrogen, phosphoric acid, and potash will be on the average 45, 30, and 50 per cent, respectively.

[1] Roberts, I. P., and Wing, H. H. On the Deterioration of Farmyard Manure by Leaching and Fermentation. Cornell Univ. Agr. Exp. Sta., Bul. 13. 1889.

[2] Shutt, F. T. Barnyard Manure. Canadian Dept. Agr., Cent. Exp. Farms, Bul. 31. 1898.

[3] Thorne, C. E. Farm Manures, p. 116. New York. 1914.

[4] Thorne, C. E., and others. The Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183. 1907.

Under conditions on the average farm such losses may easily rise to 50 per cent of all the constituents, and probably very much higher as regards nitrogen and potash. From one-half to three-fourths of the important elements contained in the original food fails to again reach the land. Hall,[1] quoting from Woods' experiments at Cambridge, shows that about 10 per cent of the nitrogen in the food consumed is retained by the animal. He also shows that 15 per cent of nitrogen is lost during the making, and from 10 to 25 per cent during the storage, of the manure, even under the best conditions. This gives a total loss of nitrogen amounting to from 35 to 50 per cent. If this is the loss under the best conditions, it can readily be seen that the loss on an average farm must approach 65 or 75 per cent.

Some idea as to separate losses from fermentation and leaching may be gained from data drawn from Canada.[2] In this experiment a mixture of horse dung and cow dung was divided. One-half was placed in a bin under a shed; the other half was exposed to the weather, outside in a similar bin. After a year the two portions were analyzed and the losses computed:

LOSSES FROM MANURE AFTER TWELVE MONTHS

	PROTECTED (Per cent)	EXPOSED (Per cent)
Loss of organic matter	60	69
Loss of nitrogen	23	40
Loss of phosphoric acid	4	16
Loss of potash	3	36

[1] Hall, A. D. Fertilizers and Manures, p. 198. New York. 1910.

[2] Shutt, M. A. Barnyard Manure. Canadian Dept. Agr., Cent. Exp. Farm, Bul. 31. 1898.

Evidently the losses by fermentation are very considerably augmented by exposure, especially if the rainfall is high. This waste not only is very considerable as regards the nitrogen, but is especially high as far as the organic matter is concerned. Such figures serve also to emphasize again the importance of shielding manure in storage from excessive rainfall. Some water is, of course, necessary, but too much serves only to carry away the materials already soluble or rendered soluble by fermentation.

504. Increased value of protected manure. — From the previous discussion it is evident that a well-protected and carefully preserved manure will be higher in plant-food constituents than one not so handled. Moreover, the agricultural value of such manure will be higher. This is shown by actual tests from Ohio.[1] Over a period of fourteen years, in a three-years' rotation of corn, wheat, and hay, a stall manure gave a yield 30 per cent higher than that with a yard manure, the quantities applied in each case being equal. In New Jersey, in comparing fresh manure with leached manure the former showed a gain in crop yield 53 per cent higher than the latter over a period of three years immediately following the application. Such figures are worthy of careful consideration by the average farmer.

505. The money waste of manure. — To make the seriousness of the question of waste in manures more striking, the probable losses may be calculated in money value for the United States. The entire live stock of all kinds in this country may be roughly calculated as equiv-

[1] Thorne, C. E., and others. Plans and Summary Tables of the Experiments at the Central Farm. Ohio Agr. Exp. Sta., Circ. 120. 1912.

alent in manure producing capacity to about 100,000,000 cattle, each weighing 1000 pounds. Assuming that each animal will produce manure to the value of $21 a year and that the cattle are yarded for four months, the total value of excrement produced during the yarding period would be, in round numbers, $700,000,000. If only one-third of the value of the manure is lost by mishandling, an annual waste of $230,000,000 would occur. This is a very conservative estimate regarding the losses of farm manure throughout the United States. The annual sale of commercial fertilizers in this country, probably amounting to over $100,000,000, is entirely inadequate to replace this loss.

506. Handling of manures.[1] — The ultimate consideration in a study of farm manures comprises the best methods of economic handling, both as to labor and as to the saving of the constituents carried by the product. The greater the amount of plant-food that can be saved in the manure and returned to the land, the less will be the necessity of commercial sources of these elements. Many methods present themselves as being more or less efficacious, but none are absolutely perfect, as losses by fermentation are bound to occur even though leaching is entirely prevented. Methods of handling are usually chosen because of their adaptability to particular circumstances, rather than because of the exact amount of valuable constituents that they will conserve.

[1] Good discussions of handling farm manure are as follows: Hart, E. B. Getting the Most Profit from Farm Manure. Wisconsin Agr. Exp. Sta., Bul. 221. 1912. Beal, W. H. Barnyard Manure. U.S.D.A., Farmers' Bul. 192. 1904. Roberts, I. P. The Fertility of the Land, Chapter IX, pp. 188-212. New York. 1904.

507. Care of manure in the stalls. — Considerable loss to manure occurs in the stable, due to fermentation and leaching. Before the litter can absorb the liquid, it is likely to ferment and to leach away in exceptional amounts. Therefore the first care is as to bedding, which should be chosen for its absorptive properties, its cost, and its cleanliness. The following table[1] expresses the absorptive capacity of some common litters:

ABSORPTIVE POWER OF BEDDING FOR WATER

	Per cent
Wheat straw	220
Oak leaves	162
Peat	600
Sawdust	435
Spent tan	450
Air-dry humous soil	50
Dry peat moss	1300
Muck	200

The amount of litter to be used is determined by the character of the food. If the food is watery, the bedding should be increased. In general, the litter may amount to about one-third of the dry matter of the food consumed. Sheep require about a pound of bedding a head, cattle from eight to ten pounds, and horses from six to seven pounds. No more litter than is necessary to keep the animal clean and to absorb the liquid manure should be used, as the excrement is thus diluted unnecessarily with material which often does not carry large quantities of fertilizing ingredients.

[1] Beal, W. H. Barnyard Manure. U. S. D. A., Farmers' Bul. 192. 1904.

The next care is that floors shall be tight, so that the liquids cannot drain away but will be held in contact with the absorbing materials. The preserving of manures in stalls with tight floors has been for years a common method of handling dung in England. The trampling of the animals and the continued addition of litter with the liquid and solid excrement, explain the reason for the success of the method. The following data, from Ohio,[1] show the relative recovery of food elements in manure produced on a cement floor and on an earth floor, respectively. The experiment was conducted with steers over a period of six months.

Recovery of Food Elements in Manure Produced on Cement Floor, on Earth Floor

	Per Cent	Per Cent
Nitrogen	74.7	62.4
Phosphorus	77.5	78.9
Potash	87.8	78.4

508. Hauling directly to the field. — Where it is possible to haul directly to the field, this practice is to be advised, since opportunities for excessive losses by leaching and fermentation are thereby prevented. Manure may even be spread on frozen ground or on the top of snow, provided the land is fairly level and the snow is not too deep. This system saves time and labor, and when leaching does occur the soluble portions of the manure are carried directly into the soil.

509. Cement pit. — Very often it is not convenient

[1] Thorne, C. E. The Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183, p. 199. 1907.

not possible, especially in certain parts of the year, to haul manure directly to the field. Means of storage must therefore be provided. Some farmers, if the amount of manure produced on their lands is large, find it profitable to construct manure pits of concrete. These storage pits are usually rectangular in shape, with a shed covering, and with open ends so that a team may drive in at one end and out at the other. In such a pit leaching is prevented by the covering and by the solid bottom. By keeping the manure carefully spread and well moistened, fermentation may proceed with a minimum loss of nitrogen. Some dairymen even go so far as to utilize a cistern, into which is shoveled both the liquid and the solid manure. Later, when fermentation has proceeded sufficiently, the material is pumped out and applied to the land. This method is not to be advocated in this country except under particular conditions.

310. Covered barnyard. — Another method of storage is by means of a covered barnyard. Such a yard must have an impervious bottom. The manure is spread out in the yard, and if animals are allowed to exercise here the manure is kept thoroughly packed as well as damp. The storage of manure in deep stalls, a favorite method in England, is similar to this system and has been shown to be very economical. It also affords an opportunity for the mixing of the manure from different classes of animals. The desirability of this has already been shown regarding horse and cow excrements. The advantages of trampling, as far as the keeping qualities of manure are concerned, are clearly shown by the following figures taken from the work of Frear:[1] —

[1] Frear, W. Losses of Manure. Pennsylvania Agr. Exp. Sta., Bul. 63. 1903.

Loss of Manure in Covered Sheds

	Percentage of		
	N	K_2O	P_2O_5
Covered and tramped . . .	5.7	5.5	8.5
Covered and untramped . .	34.1	19.8	14.2

Throwing manure in heaps under a shed and allowing hogs to work the mass over, is an economical practice so far as food utilization is concerned. It interferes, however, with proper and economical packing of the manure. The question to be decided is whether the added food value of the manure overbalances the extra losses by fermentation incurred by the rooting of the swine.

511. **Piles outside.**—Very often it is necessary to store manure outside, fully exposed to the weather. When this is the case, certain precautions must be observed. In the first place, the pile should be located on level ground far enough from any building so that it receives no extra water therefrom in times of storm. The earth under the pile should be slightly dished in order to prevent loss of excess water. If possible, the soil of the depression should be puddled, or, better, lined with cement.

The sides of the heap should be perpendicular, so as to shed water readily. The manure must be kept moist in dry weather in order to decrease aërobic action. Each addition of manure should be packed in place, the fresh on and above the older. This allows the carbon dioxide from the well-rotted dung to pervade the fresher and looser portions, thus quickly establishing the aërobic

conditions so essential to economic and favorable fermentation.

Placing fresh manure in small heaps in the field to be spread later, is, in the first place, poor economy of labor. Moreover, it encourages loss by fermentation, while at the same time the soluble portions of the pile escape into the soil immediately underneath. There is thus a poor distribution of the essential elements of the dung, and when the manure is finally spread, an overfeeding of plants at one point and an underfeeding at another results. A low efficiency of the manure is thus realized. This method of handling manure is not to be recommended.

512. **Distribution of manure in the field.** In the actual application of manure to the land, certain general principles should always be kept in mind. In the first place, evenness of distribution is to be desired, since it tends to raise the efficiency of the manure by encouraging a more uniform plant growth. This evenness of spreading is much aided by fineness of division. Moreover, it is generally better, especially in diversified farming on medium to heavy soils, to decrease the amounts at each spreading and apply oftener. Thus, instead of adding 20 tons to the acre, 10 tons would be applied and twice as much area covered. The applications would then be made oftener. A larger and quicker return in net crop yield per ton of manure applied would be realized. This has been strikingly shown by the Ohio experiments[1] over a test for eighteen years in a three-years rotation of wheat, clover, and potatoes, the manure being placed on the wheat and affecting the clover and the potatoes as a

[1] Thorne, C. E., and others. Plans and Summary Tables of the Experiments at the Central Farm. Ohio Agr. Exp. Sta., Circ. 120, p. 108. 1912.

residuum. The results are expressed in yield per ton of manure applied: —

YIELD TO THE TON OF MANURE WHEN APPLIED IN DIFFERENT AMOUNTS

	Wheat (Bushels)	Clover (Pounds)	Potatoes (Bushels)
4 tons to the acre . . .	8.0	177	37.3
8 tons to the acre . . .	4.1	150	19.4
16 tons to the acre	2.4	99	11.6

Not only is the increased efficiency from lower applications apparent, but a great recovery of the manurial fertility in the crops also results. The Ohio experiments have shown that in the first rotation after the manure is applied, a recovery may be expected from a treatment of 8 tons 35 to 30 per cent higher than from one of 16 tons.

Evenness of application and fineness of division are greatly facilitated by the use of a manure spreader. This also makes possible the uniform application of small amounts of manure, even as low as five or six tons to the acre. It is impossible to spread so small an amount by hand and obtain an even distribution. Moreover, a spreader lessens the labor and more than doubles the amount of manure one man can apply a day. When any quantity of manure is to be handled, a manure spreader will pay for itself in a season or two at the most.

Whether manure should be plowed under or not depends largely on the crop on which it is used. On timothy it is spread as a top-dressing. Ordinarily, however, it is plowed under. This is particularly necessary if the

manure is long, coarse, and not well rotted. It should not be turned under so deep, however, as to prevent ready decay. If manure is fine and well decomposed, it may be harrowed into the surface soil. The method employed depends on the crop, the soil, and the condition of the manure. The amount to be applied varies considerably. Eight tons to the acre would be a light dressing, 15 tons a medium dressing, and 25 tons heavy for an ordinary soil. On trucking lands, however, as high as 50 or 100 tons is often used.

518. Reinforcement of manure. — The reinforcement of farm manures is designed to accomplish two things in the handling of this product: (1) checking loss by leaching and fermentation, and (2) balancing the manure and rendering its agricultural value higher. Four chemicals may be used in this reinforcement: gypsum ($CaSO_4$), kainit (KCl, mostly), acid phosphate ($CaH_4(PO_4)_2 + CaSO_4$), and floats (raw rock phosphate, $Ca_3(PO_4)_2$).

Gypsum is supposed to act on the ammonia, changing it to ammonium sulfate, a stable compound. It is rather insoluble, however, so that its action is slow. It may be applied in the stable or on the manure pile. The rate is about 100 pounds to the ton of manure. It has no balancing effect.

Kainit is added to react with any ammonia that may be produced and also to increase the potash in the manure. It is soluble, and because of its caustic tendencies it must not come into contact with the feet of the animals. It must not be spread on the manure, therefore, until the stock has been removed. Since manure is unbalanced as to phosphorus, the agricultural value of this reinforcement is likely to be slight. Kainit is usually added at the rate of 50 pounds to the ton of manure.

Acid phosphate, when used as a reinforcing agent, is applied at the rate of 50 pounds to the ton of manure. It is soluble, and therefore becomes intimately mixed with the excrement. It adds phosphorus, in which manure is especially lacking. Its gypsum may react with the ammonia. Theoretically it should prevent loss by fermentation, as well as function as a balancing agent. It must not come into contact with the feet of farm animals.

Raw rock phosphate, or floats, is a very insoluble compound, and consequently reacts but slowly with the soluble constituents of manure. Carrying such a large percentage of phosphorus, it tends to balance the product and to raise its agricultural value. It is supposed that the intimate relationship between the phosphate and the decaying manure increases the availability of the former to plants when the mixture is added to the soil. No increased solubility, however, as determined by chemical means, has ever been so definitely shown to occur (see par. 438). The reinforcement is usually at the rate of 100 pounds to the ton of manure.

514. Benefits from reinforcing. — Experimental data have shown that these various reinforcements have no effect on the nature, function, and number of the bacterial flora. Their conserving influence, if any, when the manure is exposed, must be in checking leaching and in preventing loss of ammonia. The following figures from Ohio experiments[1] show how slight this conserving effect is. The reinforcement was at the rate of 40 pounds to the ton: —

[1] Thorne, C. E. Maintenance of Fertility. Ohio Agr. Exp. Sta., Bul. 183, p. 208. 1907.

CONSERVING EFFECT OF REINFORCING AGENTS ON MANURE EXPOSED FOR THREE MONTHS

Treatments	Value of a Ton of Manure		Percentage of Loss
	In January	In April	
No treatment	$2.19	$1.41	36
Gypsum	2.05	1.48	28
Kainit	2.24	1.46	35
Floats	2.81	2.04	27
Acid phosphate	2.34	1.65	29

It is immediately evident that kainit and gypsum do not conserve the manure, and, although acid phosphate and floats show some influence, it is slight. The principal benefit from reinforcing manure, if any, must therefore be as a balancing agent. The figures from Ohio[1] over a period of fourteen years in a rotation of corn, wheat, and hay may be taken as evidence regarding this point. The manure was added to the corn at the rate of 8 tons to the acre. The reinforcing was 40 pounds to the ton of manure in every case:—

THE REINFORCING OF FRESH MANURE

Treatment	Total Net Increased Value of Crop for the Rotation	Net Increased Value per Ton of Manure
Manure plus floats	$35.94	$4.49
Manure plus acid phosphate	38.56	4.82
Manure plus kainit	29.67	3.71
Manure plus gypsum	28.48	3.56
Manure alone	26.48	3.31

[1] Thorne, C. E., and others. Plans and Summary Tables of the Experiments at the Central Farm. Ohio Agr. Exp. Sta., Cir. 120, p. 113. 1913.

This balancing effect may be shown in another way. Let it be supposed that to 10 pounds of poultry manure having a composition of 1.6 per cent nitrogen, 1.6 per cent phosphoric acid, and 0.9 per cent potash, there are added 4 pounds of sawdust, 4 pounds of acid phosphate, and 2 pounds of kainit. The manure is rendered drier, and its composition becomes 0.8 per cent nitrogen, 3.7 per cent phosphoric acid, and 1.5 per cent potash. It is evident, from this and the data previously given, that the principal benefit of reinforcing manure lies in the balancing influence, and that acid phosphate and floats are the most desirable to use.

515. Lime and manure. — Very often it would be a saving of labor to apply lime and manure to the soil at the same time. This can readily be done with the carbonated forms. Such lime may be mixed with the manure, either in the stable or in the pile, without any danger of detrimental results. The close union of the lime and the organic matter may even increase the solubility of the former. Caustic compounds of lime, however (CaO and $Ca(OH)_2$), must be kept from manure. These active forms react with the ammonium carbonate coming from the urea, and cause the liberation of the ammonia, which may be readily lost in the air: —

$$CON_2H_4 + 2\,H_2O = (NH_4)_2CO_3$$
$$(NH_4)_2CO_3 + Ca(OH)_2 = CaCO_3 + 2\,NH_4OH$$

A stable or a shed containing manure may be at once deodorized by the use of quicklime, but only by the loss of much nitrogen, which costs on the market eighteen or twenty cents a pound. Caustic lime and manure may be applied to the same soil by applying the lime ten days or two weeks before the manure. The lime will then

have had time to leach into the soil or to largely change to a carbonate form.

516. Composting. — A compost is usually made up of alternate layers of manure and some vegetable matter that is to be decayed. Layers of sod or of humous soil are often introduced. The manure is used to supply the decay organisms and to start the action. The foundation of such a humus manufactory is usually sod, and the pile is preferably capped with earth. The compost should be kept moist in order to prevent loss of ammonia and to encourage vigorous bacterial action. Acid phosphate or raw rock phosphate and a potassium fertilizer are often added, to balance up the mixture and make it a more effective fertilizer. Lime is also introduced, to react with such organic acids as may tend to form and to interfere with proper decay. Undecayed plant tissue, such as sod, leaves, weeds, grass, sticks, or organic refuse of any kind, may thus be changed slowly to a humus which will be valuable in building up the soil and in nourishing plants. Even garbage may be disposed of in such a manner.

517. Manure and muck. — Muck soil recently reclaimed from a swamp condition is usually treated, if possible, with a dressing of manure. This is not so much for the purpose of adding plant-food as to supply decay and decomposition organisms that will break down the complicated humic compounds into such forms as may be utilized by the crop. Plenty of lime is therefore essential in muck, in order to render the effects of this inoculation effective and lasting.

518. Effects of manure on the soil. — The direct fertilizing effect of manure is by no means its greatest influence. In the first place, manure as it rots down produces humus. This humus increases the absorptive

capacity of the soil. In clays it promotes granulation, while in sands it acts as a binding agent. Under all conditions it promotes granulation and tilth. The capacity of a soil to resist drought is raised; its aëration is increased and drainage is promoted. All these changes tend to benefit plant growth and to produce those indirect fertilizing effects that are characteristic of farm manure.

From the chemical standpoint, the presence of manure in the soil tends to increase organic acids, notably carbonic acid. The soil minerals are thus rendered more easily soluble. The case of the influence of manure on the action of raw rock in the soil has already been cited. The humus, also, may combine with certain of the mineral elements and hold them in a form more easily available to crops. Nor is the chemical influence of farm manure the final effect. The modification of the soil flora can by no means be passed by. Not only are millions of organisms added by an application of manure, but those already present in the soil are vastly stimulated by this fresh acquisition of humic materials. Nitrification, ammonification, and nitrogen fixation are all increased to a remarkable degree.

519. **Residual effect of manure.** — No other fertilizing material exerts such a marked residual effect as does manure. This is partly because of its indirect physical and biological influences, and partly because of the stimulated root development of the crops grown. The greatest residual influence, however, is brought about by the slowly decomposable nature of the manure, only a small percentage being recovered in the first crop grown after the manure is applied. Hall[1] presents the following data

[1] Hall, A. D. Fertilizers and Manures, p. 210. New York, 1910.

from Rothamsted. The crop was mangolds, and the recovery of the constituents carried by the manure was very low: —

RECOVERY OF NITROGEN IN A CROP OF MANGOLDS

Treatment	Per Acre	Yield in Tons	Percentage Recovery
Nitrate of soda . .	550 pounds	27.85	78.1
Ammonium salts .	400 pounds	16.13	57.3
Rape cake	2000 pounds	20.35	70.9
Manure	14 tons	17.44	31.8

The length of time through which the effects of an application of farm manure may be detected in crop growth is very great. Hall[1] cites data from the Rothamsted experiments in which the effects of eight yearly applications of 14 tons each were apparent forty years after the last treatment. This is an extreme case; ordinarily, profitable increases may be obtained from manure only from two to five years after the treatment. The fact remains, nevertheless, that of all fertilizers farm manure is the most lasting, lends the most stability to the soil, and is really a soil builder *par excellence*.

620. **Place of manure in the rotation.** — With a number of trucking crops, the application of manure directly to the crop year after year has proved to be advisable. In an ordinary rotation, however, where less intensive methods are employed, it is evident that manure may vary in its effect according to the place in the rotation at

[1] Hall, A. D. Fertilizers and Manures, p. 213. New York. 1910.

which it is applied. This has proved to be the case with commercial fertilizers, and the fact is also becoming recognized in the economic use of farm manures.

In general, hay has derived more benefit from the residual food than almost any other crop in the rotation. At the Pennsylvania Experiment Station,[1] in a rotation of corn, wheat, and hay over a test for twenty-five years, in which manure was applied in equal amounts to the corn and wheat, the results were as follows: —

PERCENTAGE INCREASE FROM USE OF MANURE, AND VALUE OF THAT INCREASE

Treatment	Corn	Oats	Wheat	Hay
6 tons manure	37 per cent	28 per cent	73 per cent	39 per cent
Cost $9 . .	$10.85	$3.85	$9.70	$6.53

The same fact has been clearly shown in the Ohio experiments[2] covering a term of eighteen years. The query immediately arising here is: If hay responds so well to residual feeding, why not apply the manure directly to it? On this point the following figures from the Illinois Experiment Station[3] may be presented, comparing the response of corn and oats when manured to the yield of clover with the same treatment: —

[1] Hunt, T. F. General Fertilizer Experiments. Ann. Rept. Pennsylvania Agr. Exp. Sta., 1907–1908, pp. 68–96.
[2] Thorne, C. E., and others. Plans and Summary Tables of the Experiments at the Central Farm. Ohio Agr. Exp. Sta., Cir. 120, pp. 101–105. 1912.
[3] Hopkins, C. G. Thirty Years of Crop Rotation in Illinois. Ill. Agr. Exp. Sta., Bul. 125, p. 337. 1908.

Treatment	Average Production Increase		Total Value of Increase	
	Corn and Oats	Clover	Corn and Oats	Clover
Manure	11	93	$ 7.53	$10.09
Manure, lime, and phosphate	30	141	12.21	15.48

When hay is included in any rotation it is evident that the best results from manure may be obtained by placing it on this crop. This, however, is often not advisable, especially where the amount of manure is limited. A commercial fertilizer may take its place on the hay, allowing the farm manure to be utilized on special crops. When applied to hay it should be spread as a light top-dressing. When manure is used for such a crop as corn, however, it is best plowed under, as the amounts added per acre are often large. Farm manure in judicious amounts may be harrowed in or plowed under in orchards.

621. **Résumé.** — From the general discussion already presented, it is evident that barnyard manure, from the standpoint of soil fertility, is the most valuable by-product of the farm. A careful farmer will therefore attempt to utilize it in the most economical way. The handling of manure in such a manner that only a small waste will occur from the time when the manure is voided until it has reached the land again, is not an easy problem. Manure is so susceptible to the loss of valuable ingredients, both by leaching and by fermentation, that careful methods must be employed. The utilization of tight floors in the stable and of covered sheds or manure pits is to be ad-

vised. Hauling immediately to the field is a wise procedure. Yet even with the best of care a loss of from 30 to 50 per cent is often incurred. A permanent system of agriculture evidently cannot be established by simply returning all the manure possible to the land. Nevertheless, it is certainly worth the while of any farmer to use at least some care in the handling of this product. Even reasonable attention would save for the soils of this country thousands of dollars' worth of manurial fertility which is now carried away in the streams and rivers.

CHAPTER XXVII

GREEN MANURES[1]

From time immemorial the turning-under of a green crop to supply organic matter to the soil has been a common agricultural practice. Records show that the use of beans, vetches, and lupines for such a purpose was well understood by the Romans, who probably borrowed the practice from nations of still greater antiquity. The art was lost to a great extent during the Dark Ages, but was revived again as the modern era was approached. At the present time green-manuring is considered a part of a well-established system of soil management, and is given a place, where possible, in every rational plan for permanent soil improvement.

622. Effects of green-manuring. — The effects of turning under green plants are both direct and indirect — direct as to the influence on the succeeding crop, and indirect as to the action on the physical condition of the soil so treated. In the first place, certain ingredients are actually added to the soil by such a procedure. The carbon, oxygen, and hydrogen of a plant come largely from

[1] Penny, C. L. Cover Crops as Green Manures. Delaware Agr. Exp. Sta., Bul. 60. 1903.
Storer, F. H. Agriculture, pp. 137-175. New York. 1910.
Lipman, J. G. Bacteria in Relation to Country Life, Chapter XXIV, pp. 237-268. New York. 1911.
Piper, C. V. Leguminous Crops for Green Manuring. U. S. D. A., Farmers' Bul. No. 278. 1907.
Spillman, W. J. Renovation of Worn-out Soils. U. S. D. A., Farmers' Bul. No. 245. 1906.

the air, and the plowing-under of a crop therefore increases the store of such constituents in the soil. If the plant is a legume and the nodule organisms are active, the nitrogen content of the soil is also augmented. The mineral parts of the turned-under crop, of course, come from the soil originally and they are merely turned back to it again. As they return, however, they are in intimate union with organic materials, and are thus readily available as plant-food as the decay process goes on. Indeed they are much more readily available than they previously were, when the green-manuring crop acquired them. Actual additions are thus made to the soil, together with a promotion of an increased availability of the constituents dealt with.

Green manures may function also as cover crops, in so far as they take up the extremely soluble plant-food and prevent it from being lost in the drainage water. The nitrates of the soil are of particular importance in this regard, as they are very soluble and are adsorbed only slightly by the soil particles. Besides this, green manures, especially those with long roots, tend to carry food up from the subsoil, and when the crop is turned under this material is deposited within the root zone. Again, the added organic material acts as a food for bacteria, and tends to stimulate biological changes to a marked degree. This bacterial action is especially prone to increase the production of carbon dioxide, ammonia, nitrates, and organic acids of various kinds, which are very important in plant nutrition. The humus that results from this decay increases the adsorptive power of the soil and promotes aëration, drainage, and granulation — conditions that are extremely important in successful crop growth.

623. **Quantities of plant constituents added by green-manuring.** — In an average crop of green manure, from five to ten tons of material is turned under. Of this, from one to two tons is dry matter, and from four to eight tons water. Of this dry matter a great proportion is carbon, hydrogen, and oxygen — a clear gain to the soil in so far as these constituents are concerned. The amount of nitrogen added to a soil if the green manure is a legume[1] is a difficult question to decide. Much depends on the virulence of the organisms occupying the nodules. These bacteria are in turn much influenced by plant and soil conditions. Hopkins[2] estimates that about one-third of the nitrogen in a normal inoculated legume comes from the soil and two-thirds from the air. He also considers that one-third of the nitrogen exists in the roots. It is evident, therefore, that in general the nitrogen found in the tops will be a rough measure of the nitrogen fixed by the soil organisms. If this is returned to the soil, there is a clear gain of just that amount.

If the preceding assumption is correct, clover[3] would actually add to every acre about 40 pounds of nitrogen

[1] Smith, C. D., and Robinson, F. W. Influence of Nodules on the Roots upon the Composition of Soybean and Cowpeas. Mich. Agri. Exp. Sta., Bul. 224. 1905.

Hopkins, C. G. Alfalfa on Illinois Soil. Illinois Agr. Exp. Sta., Bul. 76. 1902.

Hopkins, C. G. Nitrogen Bacteria and Legumes. Illinois Agr. Exp. Sta., Bul. 94. 1904.

Shutt, F. T. The Nitrogen Enrichment of Soils through the Growth of Legumes. Canadian Dept. Agr., Rept. Centr. Exp. Farms, 1905, pp. 127-133.

[2] Hopkins, C. G. Soil Fertility and Permanent Agriculture, p. 223. Boston, 1910.

[3] Penny, C. L. The Growth of Crimson Clover. Delaware Agr. Exp. Sta., Bul. 67. 1905.

per ton, alfalfa about 50, cowpeas 43, and soy beans 53 pounds. These figures, even though they may be far from correct, at least give some idea as to the possible addition of nitrogen by green-manuring practices, and show how the soil may be enriched by such management. As in the case of farm manures, the indirect effects of such a procedure may override the direct influences, making the use of legumes as green-manuring crop less necessary than at first thought might be supposed.

524. Decay of green manure. — As a green crop enters the soil, the process of its decay is the same as that of any plant tissue that becomes a part of the soil body. The organisms that are active are those common to the soil, together with such bacteria as are carried into the soil on the turned-under crop. The decay should be accomplished under aërobic conditions so that only beneficial products may result. Plenty of water is a necessity, as otherwise the soil would be robbed of a part of its available moisture in facilitating the process of decay. When proper decay has occurred, end products should result which can be utilized as plant-food. The intermediate compounds that are formed should yield a black humus, should readily split up into simple compounds, and should be in general beneficial, both directly and indirectly, to crop growth. The decay of green manure under conditions of poor drainage and improper aëration is likely to cause the generation of materials detrimental to the proper development of plants.

525. Crops suitable for green manures. — The crops that may be utilized as green manures are usually grouped under two heads, legumes and non-legumes. Some of the common green manures are as follows: —

Legumes		Non-legumes
Annual	*Biennial*	
Cowpea	Red clover	Rye
Soy bean	White clover	Oats
Peanut	Alsike clover	Mustard
Vetch	Alfalfa	Mangels
Canada field pea	Sweet clover	Rape
Velvet bean		Buckwheat
Crimson clover		
Hairy vetch		

When other conditions are equal, it is of course always better to choose a leguminous green manure in preference to a non-leguminous one, because of the nitrogen that may be added to the soil. However, it is so often difficult to obtain a catch of some of the legumes that it is poor management to turn the stand under until after a number of years. Again, the seed of many legumes is very expensive, almost prohibiting their use as green manures. Among the legumes most commonly grown as green manures, cowpeas, soy beans, and peanuts may be named. Many of the other legumes do not so fit into the common rotations as to be handily turned under as a green manure.

For the reasons already cited, the non-legumes have in many cases proved the more popular and economic as green manures. Rye and oats are much used because of their rapid, abundant, and succulent growth and because they may be accommodated to almost any rotation. They are hardy and will start on almost any kind of a seed bed. They are thus extremely valuable on poor soils. Often the value of such a green manure as oats is greatly increased by sowing peas with it. The advantages of a legume and a non-legume are thus combined.

526. When to use green manures. — The indiscriminate use of green manures is of course never to be advised, as the soil may be injured thereby and the normal rotation much interfered with. When soils are poor in nitrogen and humus, they are very often in poor tilth. This is true whether the texture of the soil be fine or coarse. The turning-under of green crops must be judicious, however, in order that the soil may not be clogged with undecayed matter. Once or twice in a rotation is usually often enough for such treatments. Proper drainage must always be provided. In regions where the rainfall is scanty, very great caution must be observed in the handling of green manures. The available moisture that should go to the succeeding crop may be used in the process of decay, and the soil left light and open, due to an excess of undecomposed plant tissue.

527. When to turn under green crops. — It is generally best to turn under green crops when their succulence is near the maximum. In this case a large quantity of water is carried into the soil, and the draft on the original soil moisture is less. Again, the succulence encourages a rapid and more or less complete decay, with the maximum production of humus and end products. The plowing should be done, if possible, at a season when a plentiful supply of rain occurs. The effectiveness of the manuring is thereby much enhanced.

528. How to turn under green material. — In general, in turning under green manures the furrow slice should not be thrown over flat, since the green crop is then deposited as a continuous layer between the surface soil and the subsoil. Capillary movement is thus impeded until a more or less complete decay has occurred, and the succeeding crop may suffer from lack of moisture.

The furrow ordinarily should be turned only partly over, and thrown against and on its neighbor. The green manure is then distributed evenly from the surface downward to the bottom of the furrow. When decomposition occurs the humic materials are evenly mixed with the whole furrow slice. Moreover, this method of plowing does not interfere with the capillary movements of water, and in actual practice is a great aid in drainage and aeration.

529. **Green manures and lime.** — The decay of organic matter in the soil is always accompanied by the production of organic acids. Such acids tend to form in large amount, especially if the fermenting matter is of a succulent nature. The need of plenty of lime under such conditions is clearly apparent, as a soil of a neutral or an acid character may assume a bad condition during the process of humic decay. Lime may be added to the green-manure seeding and be turned under with that crop. The amendment would thus be in very close contact with the decaying vegetable tissue. Ordinarily, however, the application of lime at some point in the rotation is sufficient.

530. **Green manure and the rotation.** — Very often it is somewhat of a problem as to when, in an ordinary rotation, a green manure may be introduced so that it may fit in well with the crops grown. In a rotation of corn, oats, wheat, and two years of hay, a green manure might be introduced after the corn. This would not be a very good practice, however, as a cultivated crop should usually follow a green manure so as to facilitate decomposition and decay. In such a rotation the plowing-under of the hay stubble is really a form of green-manuring, there being a considerable accumulation of roots,

stubble, and aftermath on the soil. When a rotation of this kind is used it is better either to supply organic matter in other ways, or to alter or break the rotation in such a manner as to admit of a more advantageous use of green crops.

Where trucking crops are grown and no very definite rotation is adhered to, green-manuring is easier. It is especially facilitated when cover crops are grown, as in orchards. Soiling operations also favor the easy and profitable use of green manures. In general it may be said that the organic matter obtained from such a source should be supplemented by farmyard manures when possible. A better balanced and richer soil humus is more likely to result.

CHAPTER XXVIII

LAND DRAINAGE

Land drainage [1] is the process of withdrawing from the soil the superfluous or gravitational water occurring in the larger spaces within the normal root zone. Excess moisture in the soil interferes with ventilation, keeps down the temperature, and seriously disturbs the physical nature of the soil. Any means that permits the free flow from the soil of the gravitational water affords drainage. Many methods are used, according to circumstances. Indications of the need of drainage are the presence of free water in the surface soil and in excavations into the

[1] Elliott, C. G. Engineering for Land Drainage. New York. 1912.

Fauré, L. Drainage et Assainissement Agricole des Terres. Paris. 1913.

King, F. H. Irrigation and Drainage, Part II. New York. (Revised edition. 1903.)

Klippart, J. H. Principles and Practice of Land Drainage. Cincinnati. 1884.

Woodward, S. M. Land Drainage by Means of Pumps. U. S. D. A., Office Exp. Sta., Bul. No. 243. 1911.

Warren, G. M. Tidal Marshes and their Reclamation. U. S. D. A., Office Exp. Sta., Bul. No. 240. 1911.

Elliott, C. G. Drainage of Farm Lands. U. S. D. A., Farmers' Bul. No. 187. 1904.

Miles, M. Land Drainage. New York. 1892.

See also the following bulletins of state experiment stations: Michigan, Sp. 65; Maryland, 180; New York (Cornell), 254; Utah, 125; Wisconsin, 138, 199, 229; Ontario, Canada, 174, 175.

subsoil; and the tendency of the soil to puddle and bake when dry. When the wetness is prolonged, the accumulation of organic matter in the surface soil imparts a dark color. Poor drainage causes a mottled color in the subsoil, and in extreme cases a pale gray color resulting from excessive leaching. When the land is in crops the wet places are recognized by their miry condition in early spring and after rains, and by the slow starting of the crop. In meadows the grass is often winterkilled, leaving only those weeds that can withstand the conditions. Heaving of soil is another indication of wetness. In tilled crops the wet spots are often marked by the small growth of the plants and by curled, wilted leaves in dry periods. In orchards weakened and missing trees are in many cases an indication of defective drainage, especially in the subsoil, where the roots of older trees seek to develop.

Steeply sloping hill land may need drainage quite as much as flat land if it has a compact subsoil overlaid by a porous topsoil. Water is then trapped in the soil, and is removed very slowly by percolation on top of the hard subsoil and by evaporation. It is wet land in need of drainage.

631. Extent of drainage needed in humid regions. — The amount of farm land in need of some drainage is very large. Besides the land commonly designated as swamp and marsh, there are very large areas of land devoted to crop production, the yields from which are reduced by the excess of water that they contain at certain seasons of the year. The extent of swamp land varies in different countries, but is likely to aggregate about five per cent of the total area. The cropped land in need of some drainage is very much larger, and roughly aggregates three-fourths of the total improved land surface. The temporary wetness

that much land experiences is often more injurious than the prolonged wetness of swamp land. On the latter there is no loss except on the investment value of the land, which is likely to be low. On the tilled land, however, a considerable sum of money is expended for labor, seed, and perhaps fertilizers and manures, without corresponding returns. The loss under these conditions may be heavy. For the ordinary farm and garden crops, the fluctuation of the soil moisture from a condition of somewhat prolonged saturation to the dry and often hard condition that usually results is exceedingly difficult to withstand. Drainage is concerned not only with the surface and the topsoil water, but also with the subsoil water to the depth to which the roots of crops normally penetrate.

632. History of drainage. — The need for soil drainage in the production of the ordinary farm and garden crops on many soils has been recognized from the beginning of historic times. The old Roman husbandman Cato,[1] and his successors of the next ten centuries, in their writings on agriculture pointed out the importance of draining wet soil, and Cato explains how bundles of faggots should be buried in trenches in the land. In western Europe[2] artificial drainage has been practiced for some hundreds of years. In England within the last two hundred years drainage by means of pipes has become a general practice.

The practice of underdrainage by means of clay tile was begun in America in the early part of the nineteenth

[1] Cato, M. P. Roman Farm Management by a Virginia Gentleman. New York. 1913.

[2] Elliott, C. G. Engineering for Land Drainage. New York. 1912.

Miles, M. Land Drainage, Chapter VI. New York. 1892.

French, H. F. Farm Drainage, Chapter II. New York. 1859.

century. John Johnston,[1] a Scotchman living near Geneva, New York, carried out the most extensive of these pioneer enterprises, beginning about 1835. A very thorough system of tile drains, aggregating about sixty miles in length, was installed on his farm of three hundred acres, and these drains are still in operation and are producing excellent results.

633. **Effects of land drainage on the soil.** — The need and value of thorough drainage of the soil can often be better appreciated after a careful summary of its effects on the properties that determine crop growth. From a study of these it may be seen that for the production of the ordinary upland crops a reasonable amount of soil drainage is the first requisite. It may well be termed the foundation of good soil management. The more noticeable effects are as follows: —

1. Drainage permits the development of the granular structure in soils, especially in those containing much clay, and thereby permits the creation of a much better tilth. This tilth is brought about by the frequent changes in moisture content of the soil made possible by drainage, coupled with other natural and artificial agencies, as has already been explained. As a result the soil maintains the open and friable condition favorable for the absorption of rain water, and the circulation of the water in the spaces in the soil without interference with the crop roots. The tendency of the soil to puddle and form large, hard lumps is reduced.

2. The withdrawal of the excess water from the larger spaces in the soil permits the admission of air into those

[1] Mellon, C. E. History and Results of Drainage on the John Johnston Farm. Proc. New York State Drainage Assoc., pp. 37-42. 1912-1913.

spaces. This results in better ventilation. The free movement downward through the soil of the waves of saturation accelerates the process of deep soil ventilation by driving the contaminated air out through the underdrains while fresh air is drawn in behind the wave of soil moisture.

3. The removal of the excess moisture by drainage permits the soil to maintain a higher average temperature. The high specific heat of water as compared with the soil causes the presence of water to be the chief determining factor in soil temperature. Further, the process of evaporation of the excess water from the soil requires a tremendous amount of heat. The use of solar heat to warm useless water and to remove it by evaporation is avoided by draining away this excess. Drained soil not only maintains a higher average temperature in summer, but warms up earlier in spring to a temperature for planting seeds. This gives a longer growing season.

4. The improved ventilation resulting from drainage permits the roots of plants to penetrate deeper into the soil, where they come in contact with a larger supply of moisture and food. One of the indications of the need of drainage is the shallow root development of crops. Stagnant water in a saturated soil is as resistant to the penetration of upland crops as is the hardest rock (see Fig. 63).

5. The improved physical condition of the soil that results from drainage permits the retention of a larger amount of film water, and this, in time of drought, results in a much larger available supply of moisture to the crops.

6. The improved physical condition of the soil permits better internal circulation of water, by which the films are

removed and the excess water is permitted to pass away quickly in the drainage channels.

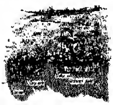

FIG. 63.—Area of land nearly level, but having compact subsoil with undulating subsurface, thereby causing wet pockets that force plants to form short roots. Weeds are abundant in such areas. Drainage removes the water and permits deeper penetration of the plant roots, thus enlarging their feeding area.

7. The improved ventilation and higher temperature due to drainage promote the activity of decay organisms, by which fresh organic matter is changed into forms that may be used as food by crops. This aids in the formation of humus, with its beneficial physical effects on the soil.

8. The higher temperature, better ventilation, better distribution of moisture and of decayed organic matter, together with the deeper penetration of roots, make available a larger amount of mineral elements from the soil particles.

9. It may now be recognized that there is a distinct sanitary aspect to soil management. The accumulation of materials of a toxic nature is promoted by poor drainage, and their destruction is hastened, and perhaps in part their formation is prevented, by the conditions that accompany good soil drainage.

10. Drainage reduces heaving. Heaving, or the lifting of crops by frost action in the soil, indicates the presence

of too much moisture in the soil in proportion to its pore space. When water freezes it expands one-eleventh of its volume. If the soil is too nearly saturated, this expansion is expressed at the surface of the soil by a lifting, or heaving, which is exceedingly injurious to most crops that pass the winter in the soil. It breaks their roots and gradually lifts the smaller plants out of the ground if the process is many times repeated. When the soil is drained so that free air spaces are distributed through the mass, the expansion of the water as it freezes is taken up in these spaces without heaving at the surface.

11. Drainage reduces erosion of soils by withdrawing the water through the soil instead of permitting it to accumulate to the point where it must move over the surface, often with serious erosive action. In order that the drains may be efficient, the soil above the drains must be sufficiently porous to permit the removal of the water as fast as it accumulates.

12. Thorough soil drainage greatly increases the efficiency of all equipment and practices used in crop production on the farm. There is a longer time in which to do the work, a longer season in which the crop may grow, and usually less labor is required in order to fit the land and keep it properly tilled. Further, the crop matures more evenly and is likely to be of better quality. The need for a commercial fertilizer is reduced because of the higher efficiency of the soil.

13. Prompt and thorough drainage of a wet soil results in a large increase in yield and quality of crops. All the common farm, garden, and orchard crops are injured by a saturated condition of the soil, and the changes that accompany the correction of that condition permits a large growth of the plants. The fundamental nature of

those changes, and therefore the basic importance of good drainage of the soil, is indicated by this summary of effects. Even where ordinary yields of crops can be grown, improved drainage will usually increase the yield 10 per cent or more; and increases of several hundred per cent are in many cases realized where the conditions before drainage were particularly bad. Land in need of drainage is in many cases fertile in all other respects, and when the soil moisture is properly adjusted it responds with large yields. Proper drainage should be the starting point in any permanent improvement of the soil.

534. Methods of drainage. Two general methods of drainage are employed: (1) open ditches, and (2) closed drains, or underdrains.

Open ditches are most satisfactory where the volume of water to be moved is very large. The general drainage of a region is usually carried in open ditches. They are used where the land is exceedingly flat, and especially if the land level is very near the level of the water in the outlet channel so that only a small head can be developed. They are used also where a temporary result is desired.

There are many objections to open ditches, either large or small, especially as applied to tilled land. They waste a considerable area of land in the channel and on the banks, and they interfere with free tillage operations. In the case of small field ditches this interference is serious. The ditch bank promotes the growth of weeds. The shallow surface trenches commonly used to remove standing water from the land are of very low efficiency, since they do not remove the water from the subsoil and often are so shallow that the surface soil remains almost saturated. Water flows slowly in such rough, irregular channels.

The cost of maintenance of a system of open ditches is heavy, because of erosion, the accumulation of silt, and the growth of weeds, all of which make frequent repairs necessary.

Underdrains when properly constructed are more permanent than open ditches and cost less for maintenance. They do not interfere with surface operations. The better grade gives them a relatively larger carrying capacity than open ditches have, and their greater depth below the surface permits much higher efficiency in the removal of excess moisture from the root zone.

585. Construction of small open ditches. — Small field ditches may be used in the field to remove small accumulations of surface water. They usually consist of a furrow run in the lowest parts and made with a large single shovel plow, with a turning plow, or with a two-way plow having moldboards to turn the soil on either side. Another modification in the construction of open ditches, which is frequently combined with the foregoing, is the use of "dead furrows." The land is plowed in narrow beds two or three rods in width, with a deep "dead" furrow between each which drains off some of the surplus water from the higher parts of the intervening area. A further modification is sometimes used in planting cultivated spring crops on wet land. Ridges are thrown up along each row and the seed is planted on these ridges. The intervening trench affords some drainage.

586. Construction of large open ditches. — Where larger volumes of water must be removed, a larger channel is necessary, its size being determined by the area to be drained, the grade of the ditch, its length, its straightness, and the smoothness of the sides and bottom. The ideal shape for the ditch for the largest carrying capacity is a

semicircle. In this form the ditch is one-half as deep as it is wide at the surface. This brings the minimum surface in contact with the moving water. The tendency of the banks to cave near the top, as well as the difficulty of constructing such a form, has led to the modification of the walls to an inclined slope that is normally one to one, or an angle of forty-five degrees. This angle is further modified by the nature of the soil through which the ditch passes, and is steeper in clay soil and less steep in loose sandy soil. Where the land is very flat and near the level of the water in the outlet channel, it may be desirable to deepen the ditch considerably below the minimum level of water in order to increase the flow during freshets.

The shape may be further modified where the volume of water to be carried varies excessively. A wide channel may be provided to accommodate the flood water, and in the bottom of this channel a smaller channel may be provided for the normal flow, of such a size that it is more likely to be kept clean and free than would a ditch of larger cross section in which the water would be shallow.

An open ditch should be kept as straight as possible so as to avoid erosion of the banks where turns occur. Change of direction should begin gradually and should have the maximum curvature at the middle of the turn. It should then pass gradually on into the straight line of the new direction.

The grade will naturally conform in a large measure to the surface of the ground, but it may need to be modified from the natural grade where the slope is so steep as to cause serious erosion. This difficulty receives special attention in constructing canals to carry irrigation water. Sandy soils having low cohesion are most subject to

erosion on high grades. Fine-textured clays are least affected by erosion. The grades and rates of flow that are permissible depend largely on the size of the ditch. A velocity of three feet a second is usually the maximum that is permissible. It may be a little higher in clay, and should be a third lower in silt and fine sandy loam. This rate of flow may be attained in ditches where the water is several feet deep by a fall of only six inches to a foot a mile. In small ditches where the water is a foot or less in depth the grade may be from fifty to sixty feet a mile, and in heavy clay, especially if it is compact and stony, a still higher grade will not cause serious washing.

These limits depend to a large extent on the amounts of sediment that the water carries. Material in suspension greatly increases erosive action on the ditch walls.

In constructing open ditches care should be taken to deposit the earth several feet back from the edge of the channel. This is desirable for two reasons: first, it removes the weight from the unsupported bank, where caving is very likely to occur when the soil is saturated; second, it provides a larger throat for the stream should it be inclined to overflow.

Another method of constructing an open ditch, especially in wet grass land, is to form a broad, shallow channel by the use of a road scraper. The earth is gradually worked back a rod or more, and the walls are so flat, even with a ditch three feet deep, that crops grow and may be collected in the bottom of the ditch. This system reduces the loss of land and the interference with farm operations.

687. **Construction of early types of underdrains.** — Any material or condition that affords an underground passage for the flow of water measurably fulfills the func-

tion of an underdrain. Many methods and materials have been employed. One used in England in clay soil is termed mole drainage. A plow having a long, thin shank, with a molelike or cigar-shaped point at the bottom, is slowly drawn through the soil by teams or a capstan. The passage formed persists for several years in the finer and more coherent classes of soil, and may do good service. Soil free from stones and having a considerable degree of plasticity is necessary for this method to have much value.

In ancient times, and in pioneer days in America, bunches of faggots, brush, poles, rails, straw, and wooden boxes of triangular or square shape, have been extensively employed for underdrainage and have been very useful. They may still have some use, but they have generally been superseded by more permanent, if not more efficient, materials.

538. Stone drains. — Wherever stones are abundant they have been placed in trenches in some manner and often have served for many years to facilitate the removal of excess water from the soil. Where there are flat stones they may be arranged to form a continuous throat. Several systems of arrangement have been used. All throated drains are more likely to be closed by sediment than a drain with no single, distinct throat. Perhaps the safest arrangement is to place flat stones on edge in the trench, with their faces parallel to one another and to the walls of the ditch, depending on the irregularities between their faces for the flow of the water. Flat stones are placed over the top of the vertical stones. Where round stones are available the safest method is to place them in the trench without any arrangement except to put the small stones on the surface. The water will find

its way through the openings. All stone drains are likely to be of short duration because of obstructions that develop in the channel by the accumulation of sediment, often promoted by the burrowing of animals. The throat of a ditch, to receive stone or brush, should be relatively large (see Fig. 64).

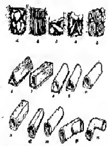

FIG. 64.—The most common types of drainage tile and other materials used for land drainage: (1), cobblestones with smaller pieces of stone on top; (2), flat stones placed lengthwise and parallel to line of ditch; (3) and (4), triangular drains constructed of flat stones used in different ways; (5), pole drain; (6), triangular box drain; (7), square box drain. Note construction for admission of water along lower edge; (8), horseshoe tile laid on a board; (9), horseshoe tile, bottom attached; (10), single sole tile with round opening; (11), double sole tile; (12), hexagonal tile; (13), round tile; (14), Y shaped junction piece; (15), elbow piece.

839. **Tile drains.** Modern underdrainage is usually accomplished by means of short sections of pipe of burned clay or concrete, placed in the ground sufficiently deep to lower the water table in the subsoil to the desired depth within two or three days. They are given an accurate grade, and this, coupled with the smooth, hard channel which is not subject to erosion, makes them a very effi-

cient as well as a very permanent means of land drainage at relatively small cost. If they are well installed and of good material, they should continue to operate for centuries with very little attention. As noted above, tile drains have been in continuous operation in America for seventy-five years and are still firm and efficient.

540. **Quality of tile.** There may be a considerable range in the quality of tile made of either clay or concrete. Clay tile is made of several grades of clay and sand mixed and burned at a high temperature. Material that is fused slightly is thereby vitrified, and forms a tile having a very dense, impervious wall. This is vitrified tile. Burned at a lower temperature the walls are more porous and less resistant. Some material does not fuse at any temperature to which it may be raised, and produces a tile having soft, porous walls. This makes soft, or brick, tile. Still another grade of tile is made of clay — usually fire clay — dipped into a salt solution before firing. This gives a smooth glaze, commonly seen in sewer tile. This is glazed tile.

Of the three grades mentioned, the vitrified tile is usually the best because of its strength and resistance to the destructive agencies in the soil. The most noticeable of these agencies is frost. Even burned clay cannot resist the destructive action of freezing water. Any tile that has walls porous enough to absorb an appreciable amount of water — and the larger the amount, the greater is the danger — will, if frozen and thawed a few times, be shattered into flakes. The walls of soft tile will absorb capillarily from 8 to 20 per cent of moisture, and under the action of frost will go to pieces rapidly. Glazed tile is less injured, especially when the glaze is intact; but once a crack has formed the tile is rapidly destroyed.

The vitrified tiles have walls so dense that they absorb less than 3 or 4 per cent of moisture, and often less than 2 per cent, so that they are much less vulnerable to frost action. Good tile should be well formed and should give a clear ring when struck with a hammer.

Concrete tile of good quality may be made, but the quality is normally inferior to that of the best vitrified tile. The porosity is likely to be 5 to 10 per cent. To make good cement tile requires a rich proportion of cement, good sand, and as wet a mixing and molding as is practicable. Several machines of both farm and factory size are in the market for molding concrete tile.

Water enters tile through the joints, not through the walls. Even the most porous tiles having a high absorption do not permit an appreciable amount of water to pass through the walls. Therefore, soft tiles have no higher efficiency than vitrified tiles, and, owing to the risk of freezing, the effectiveness of a line of porous tiles is much jeopardized. Since water enters at the joints of the tile, short lengths are more efficient than long lengths. The usual length of sections of tile under 12 inches in diameter is 12 to 13 inches. In larger sizes, where the carrying function predominates over the collecting function, lengths of 2 feet are employed.

541. **Shapes of tile.** — Tile should have a round opening and a round or a hexagonal exterior. A flat-bottomed opening is objectionable because it reduces the flow and promotes the accumulation of sediment. U-shaped tiles with flat sides are called horseshoe, or single-sole tile. This shape is unsatisfactory. Tiles are often warped in the process of drying and burning, and the last-named shape does not allow a close joint to be formed by turning the tile. Round and hexagonal shapes permit turn-

ing until a good joint is formed. An earlier type was the U-shaped tile laid on a board. These tiles are easily broken by the pressure of the earth. They are no more efficient than the ordinary round tile.

542. **Protection of joints.** — Soil water should enter the tile at the lower side of the joint. Any unusual opening in the joint should be on the lower side. If the soil has low coherence, such as may be the case with fine sand and silt, the upper half of the joint should be protected against the entrance of sediment. A cap of paper or of burlap cloth, two or three inches wide and long enough to cover the upper half of the joint, may be used.

Other methods of protecting joints are to cover them with clay, thick cement mortar, or the sod and granular soil from the surface. The last named is most commonly employed. Filters may be constructed by placing around the tile a layer of coarse sand or gravel, cinders, straw, or leaves. Where the soil is of a serious quicksand nature (clean, fine sand or silt filled with water), it may be desirable to place a bed of gravel or cinders under the tiles as well as around them. The entrance of water from the lower side of the joint in small trickles will generally prevent any difficulty from sediment. Water should flow from a drain approximately clear, and any other condition usually indicates a too rapid entrance of water. Where the soil is a fine clay with high cohesion, the ends of tiles should not be so close together as in loose soil. The tops may sometimes be separated an eighth of an inch with entire safety. In such cases it is especially important to return the soil to the trench in a dry condition and to place the topsoil next to the tile.

543. **Entrance of roots into tile.** — The entrance of roots into the joints of tile drain sometimes causes an

obstruction by breaking up into such a mass of fine rootlets that the tile is finally closed. Any kind of tree or plant may cause this difficulty if permitted to develop under certain conditions. Trouble from roots occurs only where the tile carries water from a spring or some other continuous source, so that in dry periods the water may leak out at the joints into the adjacent dry soil. This leads the roots in the direction of the tile. In the absence of such a spring, plant roots do not appear to interfere with drains. Where a drain carrying water continuously comes near a tree, especially if the adjacent soil is likely to become dry, the joints of tile should be closed by cement.

544. Protections of joints on curves. Special care may be needed in order to protect the joints on turns where the outer side may be too open. The larger the size of the tile, the longer will be the opening on a given curve. Short turns should not be made. Stones are usually unsafe material to place around the joints of a tile under such conditions, especially in soil that is likely to erode easily. If so used, special care should be employed to protect the joints with caps.

545. Foundation for tile.—Tiles should have a firm foundation, and if the bottom of the ditch is soft it may be advisable to bed them in sand or cinders or lay them on a board. Soft muck and quicksand make this most necessary. Ordinarily the bottom of the trench is finished on the undisturbed earth, which affords a firm setting.

546. Arrangement of drainage systems.—The arrangement of a system of underdrains should be determined by the slope of the land and the structure of the soil. No fixed rule can be laid down. The aim must be to place the drains in the line of movement of water in

the soil, and thereby intercept its flow. The need of drainage may arise from several conditions. It is always indicated by the occurrence of a stratum of rather compact soil which intercepts the natural flow of water and brings it within the root zone. Sometimes this obstruction is near the surface; sometimes it is several feet below the surface. The water may be brought to the surface in a single spring or in a series of springs, in the latter case forming a seepage line. The retaining layer may have an uneven surface and form basins and hollows disguised by a covering of porous soil. For all these reasons, the drainage conditions of the soil and the lines of movement of water through it should be studied as fully as possible before the drainage system is planned. The main lines should first be located. Where the land is in need of drainage in parts, a few lines of tile will accomplish this. Springy holes should generally be tapped by the most direct route. Often, short wing drains may be necessary at the upper end, to collect the underground flow. (See Fig. 65.)

Where there is a line of seepage at nearly a uniform level, a drain placed across the slope at the upper edge of the wet area, and if possible cutting to the underlying hard stratum, will intercept the flow and meet the needs of the lower land. This is an intercepting system of drains.

Where the land is more nearly uniform in its need of drainage, a regular system is required and will usually result in a saving of tile. This arrangement should approximate a rectangular system, in order to avoid double drainage where lateral tile join the main line. This may of course be modified according to conditions. The line of tile should be as long as is practicable for convenience in construction. To this end, if the field

is wide in proportion to the length of the main drains, the subdrains may branch out laterally at a right angle or less. If the laterals on either side of the main drain join at the same acute angle, the "herring-bone" system

FIG. 86.—Sectional view of soil and rock formation, showing the underground movement of water and the position of resulting wet areas on the surface. In addition to the springy places, the soil is kept wet by the seepage of water along the top of the compact subsoil. This figure also illustrates the reason for locating a cross drain above the springy area in order to effect drainage. This method cuts off the water supply.

is formed. If the main drain is situated in the wettest part of the field, this system has some advantage. If the field is long and very narrow, the main drain may lie along the short side of the field, with long laterals leading up the slope. If the land is of about equal wetness on a slope, the drains should extend up and down rather than across the slope.

547. Grade of tile drains. Where the land is relatively flat or uneven, a survey should be made in order to determine the distribution and extent of the grades. This is necessary in arranging the system. Where the grades are simple, the arrangement may be determined by the eye, if the man in charge is experienced.

Tile drains operate best on a grade of one or two feet in a hundred. Larger grades are permissible, but in such cases the earth should be carefully packed around the tile in filling. Tile will operate even on the very slight grade of one or two inches in a hundred. In this case the minimum size of tile should be larger than on high grades, and the distribution of the fall should be very uniform. Every part of the operation of planning and construction should be guided by readings of an accurate level.

548. Depth of drains. — The depth of tile drains should ordinarily be from two feet to three and one half feet. The former depth should be the one for clay loam or other moderately impervious soil, and is adequate for most crops having a shallow root penetration. The greater depth should be used on sandy and gravelly soil and where deep-rooted perennials are to be grown. Under special conditions the drains may be laid deeper or less deep than these figures. On very dense clay or where a very impervious hardpan exists, the drains may be placed a little nearer the surface, since their function is primarily to remove the water trapped near the surface. To intercept deep underground flow or to secure an outlet for it, or where especially deep rooting of crops is desired, drains may be laid deeper than the normal.

Where the soil is sufficiently porous to permit reasonably free percolation of water, as in gravelly and sandy subsoils, the deeper drains operate earlier after a rain and are the more efficient. The number of drains necessary is also reduced by laying them deeper. Where the subsoil is relatively impervious, shallow drains should be installed and placed as near the top of the impervious layer as is practicable. A shallow trench should be formed in

the compact layer to receive the tile, and if its depth exceeds half the diameter of the tile special care should be taken to place the topsoil or some other porous material on the tile and around the joints in order to insure the entrance of water.

593. **Distance between drains.**—The interval between drains must be determined by the nature and the wetness of the soil and the value of the crops produced. In soil where drains must be installed at a depth of two and a half feet or less, for general farming the interval between drains must ordinarily be not more than fifty feet. Where they may be placed deeper, the interval may be correspondingly greater.

The number of feet and rods of tile required when the lines are laid regularly at a specified distance apart is given in the following table:

Distance Apart in Feet	Tile per Acre	
	Feet	Rods
20	2,178	131.50
25	1,740	105.42
30	1,452	88.00
40	1,089	65.75
50	870	52.71
80	545	32.88
100	435	26.35
150	290	17.57
200	218	13.18

Under the influence of the drains the physical nature of the surface soil and of the subsoil gradually changes and undergoes improvement. Lines of seepage develop,

and the drain gradually increases in efficiency. In heavy soil and in soils having hardpan properties, several seasons may be required for this change in the soil to spread three or four rods from the drains. The problem is to remove the excess water from the soil at the maximum distance from the drains in time to avoid serious injury to the crop.

550. Construction of drainage trenches for tile. — Trenches should be as small as possible and yet permit the ready introduction of the tile. Unless the tiles to be used are of the larger sizes, the ditch should be made from twelve to fourteen inches wide, with vertical sides. Where leveling instruments are employed, the course of the ditch is staked out and the grade cord is stretched a definite distance above the proposed grade line of the ditch, to guide the workmen. In hand digging, the earth is thrown out with a narrow-pointed spade, the loose earth

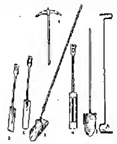

Fig. 611.—Tools for ditching. (1) and (2), ditching spades for removing the major part of the earth from the ditch; (3), grading scoop used to finish the bottom of the ditch and the grade; (4), skeleton spade adapted for use in very plastic soil; (5), shovel for removing loose earth; (6), hook used to place tile in deep, narrow trenches; (7), pick for loosening stone and hard earth.

is cleaned out with a round-pointed shovel, and the bottom is finished to a smooth, perfect grade by means of the grading scoop, which also rounds the bottom of the trench into shape to receive the tile. (See Fig. 66.) Care should be taken not to excavate the trench below the grade line, so that the tile may have a firm bed.

Horse and engine power are now very generally applied to trench digging. Several types of plows drawn by horses are available to loosen the soil, and some types are arranged to follow the grade and to elevate the loose earth out of the trench. Several types of engine-driven machines are in use where the land is not excessively stony. They cut the trench to the full depth at one operation, and are constructed so as to follow a perfect grade, so that tile may be laid as fast as the machine progresses.

561. Laying tile. — Where two lines of tile join they should come together at an acute angle, forming a Y so that the two streams of water will have the minimum interference and the collection of sediment will be prevented. If the lines are arranged at right angles, one of the strings may be turned down grade in the form of a curve in the last rod of its course, to make the proper union. Junction pieces or Y's may be bought in the smaller size of tile. They are rated by the diameter of the lateral and main branches; for example, a 3 × 6 junction indicates a three-inch lateral and a six-inch main. A lateral tile should enter the main drain with a slight drop. A small tile should enter a larger main drain at the horizontal center of the latter.

The tiles are placed in the trench by hand, or, if the trench is deep or the tiles are very large, by means of some mechanical arrangement such as a hook. Their

ends are put in line and as close together as conditions seem to indicate is necessary. Any covering or filling material is then put in place. The tile should be placed in the trench as soon as the latter is finished, and the trench should then be at least partially filled with earth in order to avoid danger from freezing or from the caving-in of the walls. The first lot of earth — usually from the surface — is carefully placed about the tiles and packed in so as to hold them in position. This is called the blinding, or back-filling. The later filling may be accomplished in any convenient way.

552. Size of tile. — The size of tile must be determined by the amount and rate at which the water must be removed, the grade of the drain, and the nature of the soil. The small lateral drains whose function is to collect the water from the soil will usually be of three or four inches internal diameter. Drains smaller than this should not be used because of their inclination to become clogged. Small tiles are relatively more affected than larger tiles by the inevitable slight imperfections in the grade. The high friction of the walls in small tiles to the moving water reduces the rapidity of flow and encourages the accumulation of sediment. In soil somewhat of the nature of quicksand, and where the grade is less than one foot in a hundred, no tile smaller than four inches in diameter should be used. As the drainage water is collected by the different lines, the size of the tiles must increase correspondingly.

553. Amount of water to be removed from land. — Many things affect the amount of water to be removed from a given area of land. The more important of these are the rainfall, the occurrence of springs, surface accumulation, the storage capacity of the soil, and rate of

evaporation. Underdrains are designed with a capacity to remove only part of the normally largest rainfall in a period of twenty-four hours. The absorptive power of the soil and its hindrance to the flow of water through its pores permits the use of a tile-drain system capable of removing from one-quarter to one-half inch of water over the drainage basin in twenty-four hours. This is termed the drainage coefficient of the area. The drainage coefficient of the system, especially if it is a large system, should be determined after careful study of the amount and distribution of the rainfall and the extent to which surface and subterranean water is accumulated.

564. Carrying capacity of a tile-drain system. The carrying capacity of a system of tile drains depends on their respective sizes, their grade, or fall, their total length, their depth in the ground, the straightness of their course, and the smoothness of the interior of the tile. Some of these factors affect the flow directly as they increase, others inversely. The two most important elements in determining the capacity of a drain are the diameter and the grade. The capacity of a drain varies as the square of the diameter. Doubling the grade increases the capacity by approximately one-third. With certain additional corrections and modifications, all the factors that affect the flow have been put together in a formula to determine the necessary size of the outlet tile for a given area. This formula, known as Poiseuille's formula, as modified by Elliott[1] for large systems, is as follows: —

[1] Elliott, C. G. Engineering for Land Drainage, Chapters VII, VIII, IX. New York. 1912.

(1) $A = \frac{Q}{C}$

(2) $Q = aV$

(3) $V = 48\sqrt{\frac{d(h + \frac{b}{n}) + \frac{d}{2}K}{l + 54d}}$

A = acres to be drained

C = coefficient of drainage selected for the area in cubic feet per second. It is determined by the depth of water to be removed in twenty-four hours

Q = quantity of water the tile will discharge, in cubic feet per second

a = area of tile in square feet

V = velocity in feet per second

d = diameter of tile in feet

l = length of tile in feet

h = head, or difference in elevation between outlet and upper end, in feet

b = sum of amounts of head in laterals, in feet

n = number of laterals

K = depth of tile below soil surface at upper end, in feet

48 and 54 are factors that take account of gravity, the size of the tile, and the roughness of the walls. The former figure is larger for tile more than twelve inches in diameter.

The first formula determines the number of acres that a given size of tile will drain, by dividing the quantity of water to be removed by the coefficient of drainage selected for the region.

The second formula determines the quantity of water possible to remove, by multiplying the area of the cross section of the tile by the velocity of flow.

The third formula is used to determine the velocity of flow of water in the outlet tile.

In a small system, where the laterals are relatively unimportant and where the soil is fairly close, the velocity formula may be much simplified as follows: —

$$V = 48\sqrt{\frac{dk}{1+54d}}$$

The term $\frac{1}{2}K$ is used only where the soil is so very porous that the ready movement of the water through the soil has an influence on the flow in the tile.

Coefficients of drainage and their equivalents in cubic feet per second of discharge are as follows: —

Depth of Water in Inches Removed in Twenty-four Hours		Cubic Feet per Second of Discharge	
Fraction	Decimal	Per Acre	Per Square Mile
1	1.00	0.0420	26.9
$\frac{3}{4}$	0.75	0.0315	20.2
$\frac{1}{2}$	0.50	0.0210	13.4
$\frac{1}{4}$	0.25	0.0105	6.7

From the above formula Elliott has calculated the number of acres of land drained by outlet tiles of different sizes and grades where the coefficient is one-fourth of an inch in twenty-four hours and where the main is 1000 feet in length: —

ACRES FROM WHICH A MAIN TILE LAID ON GRADES INDICATED MAY ADEQUATELY RECEIVE DRAINAGE WATER

DIAMETER OF TILE (IN INCHES)	GRADES TO A HUNDRED FEET IN DECIMALS OF A FOOT WITH APPROXIMATE EQUIVALENTS IN INCHES					
	½ inch	1 inch	2 inches	3 inches	6 inches	9 inches
	0.04	0.08	0.16	0.25	0.50	0.75
	Acres	Acres	Acres	Acres	Acres	Acres
5	17.3	19.1	22.1	25.1	32.0	37.7
6	27.3	29.9	34.8	38.6	50.5	59.4
7	39.9	44.1	51.1	58.0	74.6	87.1
8	55.7	61.4	71.2	80.9	106.3	121.4
9	74.7	82.2	95.3	108.4	136.1	162.6
10	90.9	106.7	123.0	140.0	170.2	211.1
12	132.3	157.7	184.6	221.1	281.8	331.3

514. Cost of drainage. The cost of tile drainage depends on many things, including especially the size of the tile, the frequency of the drains, the depth, the nature of the soil, the method of digging, and the price of labor. The cost of tile varies in different regions and increases rapidly with the size.

The following schedule will serve merely as a general guide to the range in price a thousand feet and a rod when purchased in car lots:

	SIZE (DIAMETER IN INCHES)					
	2	3	4	5	6	8
Cost a thousand feet	$10–$14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cost a rod	$.18–$.21	1.20–1.27	1.27–1.38	[illegible]	[illegible]	[illegible]

The cost for digging the trench of course varies widely. In medium soil free from stone, for a ditch two and one-

half feet deep to receive tile up to ten inches in diameter, the cost may be from fifteen cents to fifty cents a rod, with an average of about thirty-five cents. The cost can sometimes be reduced by the use of a power machine. In stony and hardpan soil the cost may be very much higher than these estimates. The deeper trench is relatively the more expensive to construct.

Laying the tile, filling the trench, and other miscellaneous operations for the smaller sizes of tile will cost at least ten cents a rod. This makes a total cost for four-inch tile of about [illegible] cents a rod, $[illegible] a hundred feet, and $[illegible] a mile.

Records are available of the cost of drainage on an extensive area of cultivated farm land in northern Ohio,[1] where the soil is chiefly a medium clay loam, somewhat stony, and where the depth was two to three and one-half feet. Some of the work was done by hand and some with the aid of a traction ditching machine. A fairly low price prevailed for tile, the sizes ranging from three to thirteen inches.

The results are as follows:

	Cost of Installing Tile Drains	
	Hand work	Machine work
Area (in acres)	40	188
Number of rods of tile	2,580	9,035
Cost of installation per rod	$0.4469	$0.3746
Average cost of tile per rod	$1.2445	$0.2445
Average number of rods to the acre	48	48
Average cost to the acre	$33.28	$28.73

[1] Goddard, L. H., and Tiffany, H. G. The Cost of Tile Drainage. Ohio Agr. Exp. Sta., Circ. 147. 1914.

656. **Storm channels.** — Where large volumes of water must be carried for a short time in addition to the normal flow, a medium-sized tile drain may be combined with an open surface channel for carrying away the flood water. The open channel is located a little to one side of the tile drain so that the latter may not be displaced by possible erosion. The open surface channel is made broad and shallow in order to avoid interference with tillage operations, and if erosion is likely to occur, it may be kept in grass.

657. **Silt basins.** — Silt basins are wells in the line of tile drains, for collecting sediment that might otherwise be deposited in the tile. The course of the drain is interrupted and a small well is sunk two or more feet below the bottom of the drain. The well extends to the surface of the ground and has a cover. The inlet drains come in at a slightly higher level than the outlet. The heavy sediment drops to the bottom, whence it may be removed from time to time. The end of the outlet tile is finished with an elbow, turned down so as to prevent the entrance of sticks or other floating material. The walls of the well may be made of wood, concrete, or brick.

658. **Surface intakes.** — The admission of surface water into a tile drain should always be managed with great care to remove the heavier sediment or other material that might obstruct the tile. Screen boxes should be used. The screen should incline to the intake at an angle of fifty or sixty degrees, so that floating material, instead of obstructing the flow, will be pushed upward out of the course.

659. **Outlets.** — As few outlets as is practicable should be constructed for tile drains, and these should have a

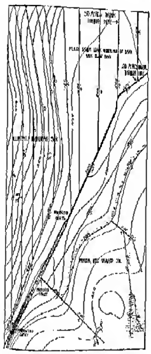

FIG. 87.—A drainage plan of an area of land exhibiting many differences as to soil, slope, and degree of wetness. Herein are shown the kinds, sizes, and arrangements of drains necessary to provide efficient drainage under the various conditions.

drop and be well protected by wing walls. Lines of drains should be connected in systems for this purpose. Unless the drain has a high grade the outlet should not be covered by water. The end of the tile should be protected by a gate or a series of rods to prevent the entrance of small animals.

580. Muck and peat soil. — Muck and peat soil should usually be drained by open ditches at first. After learning the nature of the material and the structure of the subformation, it may be found permissible to install tile in the smaller ditches. When the organic material is more than four feet deep, so that tile could not be laid on a hard bottom, much risk is involved in its use due to the excessive shrinkage of such soil when the surplus water is removed and when even moderate drying occurs. If the area is fed by springs so that the water level will be kept permanently at the base of the tile, the shrinkage will be very small and the tile may usually be laid with safety, especially if placed on boards to aid in keeping the alignment. In so-called dry peat, where the subsoil may dry out seriously in summer, the use of tile is inadvisable. In muck soil, which has a finer texture resulting from a more advanced stage of decay, tile drains may be used with greater safety.

The distance between drains in muck should be from one hundred to five hundred feet, depending much on the nature of the subsoil. Since the surface is likely to be relatively flat, nothing smaller than four- or five-inch tile should be employed and the joints should be carefully protected as described above.

Since the capillary power of muck soil is low, the water table should not be lowered more than from two to three feet, depending on the quality of the soil. While the

bottom of the open ditch may go below this level, it is often advisable to insert check gates to hold the water level when it has been lowered to the desired depth.

681. Drainage of irrigated and alkali lands. — Excessive irrigation and the occurrence of underground seepage has resulted in the water-logging of extensive tracts of arid and semiarid land, and in the serious accumulation of alkali salts in the surface soil. An effective remedy for this condition is the installation of a thorough system of drains,[1] preferably underdrains, coupled with heavy irrigation by means of which the excess salt is leached out in the drainage water. The most seriously alkaline land is now being effectively reclaimed by drainage, for the production of alkali-sensitive crops.

For this purpose drains are installed deeper than is the custom in humid regions, in order to reduce the capillary rise of moisture to the surface of the soil, where the alkali salts are deposited in injurious amounts. The drains are often placed at depths of from four to six feet. Special care is also taken to intercept the underground seepage. Sometimes the seepage water from leaky canals and reservoirs and from over-irrigation may pass long distances in porous gravel strata and rise to the surface of the land on encountering some impervious obstruction. In such cases wells may be sunk many feet to the water-bearing stratum, and the water thus conducted away in drains far enough below the surface to avoid injury to the soil.

Many special problems are encountered, such as the occurrence of hardpan — usually a stratum cemented by alkaline carbonates — and the development of a serious

[1] Elliott, C. G. Development of Methods of Draining Irrigated Lands. U. S. D. A., Office Exp. Sta., Ann. Rept., pp. 489–501. 1910.

quicksand condition of soil. The hardpan may need to be partially broken up by dynamite. The latter condition may require the placing of the tile on boards or the use of wooden box drains to keep the alignment.

Coupled with deep drainage, sufficient irrigation water is employed to produce heavy percolation, by means of which the excess salt is removed. The most alkaline land can usually be reclaimed in two or three years of leaching.

562. Vertical drainage. — A gravity outlet for drainage is sometimes difficult to provide. In such a case it may be possible to remove the drainage water through some porous stratum below the surface. There must be such a porous stratum within reach below the surface, in order to render the method of vertical drainage practicable. Basin-shaped areas without an outlet may be wet because of the accumulation of a thin layer of clay or other impervious sediment in its lowest part, beneath which at a short distance is a porous gravel or sand formation. Anything that perforates this impervious layer and keeps open the passage will afford drainage. Wells several feet in diameter may be constructed and filled with stone. Tile drains and open drains have been emptied into such structures. An opening of temporary efficiency may be formed by a charge of dynamite. The tendency of such an opening, however, is to become clogged.

A second condition under which vertical drainage may be advisable exists in a soil that is underlaid within a few hundred feet by a limestone or other porous rock formation into which the surface water may be emptied. A casing may be installed to protect the walls of the well and to reach from the surface to the porous stratum. In addition a trapped intake, coupled with a silt basin,

may be placed at the top of the well to insure its continuous operation. Extensive systems of underdrains are reported to have been discharged by this arrangement, where it might otherwise have been necessary to go a long distance in order to obtain an outlet. It should be noted that in many cases a sufficiently porous stratum is lacking in the structure of the surface portion of the earth, so that the method could not often be employed.

363. Drainage by means of explosives. — The use of explosives for promoting drainage has been proposed for three conditions: —

1. To break up a hard subsoil and possibly make a connection with a more porous stratum below, so that the soil could better handle the normal rainfall. This is closely related to the operations of subsoiling.

2. To break through a thin impervious layer in the bottom of a wet basin-shaped area. This is identified with vertical drainage described above.

3. To open up channels for drainage purposes. This use is the most extensive. By proper distribution of the charges of explosives, coupled with favorable soil and weather conditions, a very good channel can be opened by this method. It is suited only to the excavation of open ditches of medium size, three feet or more in width, and it has the greatest advantages where the land is much obstructed by stone or stumps. The force of the explosive largely clears the ditch of earth and obstructions. No very accurate grading of the bottom of the ditch can be accomplished by this method.

364. Résumé. — The removal of the excess water from the soil by any means constitutes drainage and is one of the most fundamental operations in soil management. The effects of adequate drainage are numerous

and far-reaching. In its accomplishment the physical properties of the soil and its moisture relations must be taken into account. Whether open ditches or underdrains are employed depends on the local conditions, but where practicable underdrains are always to be chosen. While the cost of drainage is a considerable sum, the improvement when well made is of long duration and the cost may therefore be distributed over a long period. The benefits accrue not only in increased crops, which are generally large, but also in the saving of expense in operation. Good drainage is the basis of good soil management.

CHAPTER XXIX

TILLAGE

While the farmer depends somewhat largely on the weathering agencies for granulation of his soil, maximum tilth can be obtained only by certain external operations. The advantages to be derived from drainage have been pointed out. The importance of the addition of lime and organic matter as a means of soil improvement has been emphasized. Yet, after all these have been provided, a further fundamental practice remains to be followed. This practice is tillage, or the manipulation of the soil by means of implements so that its structural relationships may be made better for crop growth. Tillage is so general in its application, so pronounced in its effects, and so complex in its modes of operation, and has to do with so many machines employing different mechanical principles, that it requires discussion by itself.

565. **Objects of tillage.** — Tillage aims to accomplish three primary purposes: (1) modification of the structure of the soil; (2) disposal of rubbish or other coarse material on the surface, and the incorporation of manures and fertilizers into the soil; (3) deposition of seeds and plants in the soil in position for growth.

The most prominent of these purposes is the modification of the soil structure. This affects the retention and movement of moisture, aëration, and the absorption and retention of heat, and either promotes or retards the

growth of organisms. Through all these factors the composition of the soil solution, and finally the penetration of plant roots, is influenced. The creation of a soil mulch is merely a change in the structure of the soil at such times and in such a manner as will prevent evaporation of moisture. For this reason it is essential to understand the relation of soil structure to the movement of moisture in managing the mulch. In fine-textured soils, in which the granular or crumb structure is most desired, tillage may have an important influence on the formation or destruction of granules. As has been pointed out, any treatment that increases the number of lines of weakness in the soil structure facilitates the action of the moisture films and the colloidal material in solidifying the soil granules. Tillage shatters the soil and breaks it into many small aggregates which may be further drawn together and loosely cemented as a result of the evaporation of moisture. The more numerous the lines of weakness produced, the more pronounced is the granulation; and, conversely, the fewer the lines of weakness produced, the more coarse and cloddy is the structure.

656. Implements of tillage. — The implements adapted to the manipulation of the soil are very numerous, and embrace many types. Many operations are comprehended by the term tillage, which includes the use of all those implements that are used to move the soil in any way in the practice of crop production. It includes the smallest hand implements as well as the heaviest traction machinery.

657. Effects on the soil. — All these operations may be divided into two groups, according to their effect on the soil, — those that loosen the soil structure, and those that compact the soil structure. In the subsequent

paragraphs of this chapter the effect of the commoner types of tillage implements on the soil are pointed out as a guide to their selection for the accomplishment of a desired modification. Good soil management consists, first, in analyzing the soil conditions, in order to determine the change that should be effected, and second, in the selection of the implement or other treatment that will most readily and economically accomplish the object.

568. Classes of tillage implements. — According to their mode of action, tillage implements may be divided into three groups, — plows, cultivators, packers and crushers.

569. Plows. The primary function of a plow is to take up a ribbon of soil, twist it upon itself, and lay it down again bottom side up, or partially so. In the process two things result: (1) if the soil is in proper condition for plowing, it will be shattered and broken up; (2) the soil is partially or wholly inverted, and any rubbish is put beneath the surface.

570. Pulverizing action of the plow. — In twisting, the soil tends to shear into thin layers, as already pointed out (par. 198). These layers are moved unequally upon each other, as the leaves of a book when they are bent. The result should be a very complete breaking-up of the soil. How thorough the breaking up will be will depend on (1) the condition of the soil, and (2) the type of plow. As to the condition of the soil, there is a certain optimum moisture content at which the best results will be obtained. That condition of moisture is the one that is best for plant growth. Any departure from this optimum moisture content will result in less efficient work. It has been said that, in proportion to the energy required, the plow is the most efficient pulverizing implement used by the

former. The optimum moisture content for plowing is indicated by that moist state in which a mass of the soil, when pressed in the hand, will adhere without puddling but may be readily broken up without injury to the intimate soil structure. This is a much more critical stage for fine-textured soils than for coarse-textured ones. Sandy soils are not greatly altered by plowing when out of optimum moisture condition. On the other hand, if a clay is plowed when it is saturated with water, it will be thoroughly puddled and will dry out into a hard, lumpy condition. Such a structure requires a considerable time to remedy.

671. Types of plows (Fig. 68).—There are two general types of turning plows, the common moldboard plow and the disk plow. Their mode of action is quite different, although, so far as the soil is concerned, the result is much the same. The moldboard plow seems to have a wider application than the disk plow, but both have a particular sphere of usefulness.

The disk plow is essentially a large revolving disk set at such an angle that it cuts off and inverts the soil, at the same time pulverizing it fairly effectively after the manner of the moldboard plow. One advantage claimed for the disk plow is its lighter draft for the same amount of work done, due to its having rolling friction in the soil instead of sliding friction. In practice it appears to be especially effective on very dry, hard soil and in turning and covering rubbish.

For any given texture of soil and any given soil condition, there is a type of plow, a shape of moldboard, and a depth of furrow slice, that will give the best results. This fact is to be kept constantly in mind in plowing soil. Sod land requires a different shape of plow from fallow

land, sandy land from clay land. Rubbish on the surface may be handled by one plow and not by another. On wet clay one should use a different shape of plow from that which is preferable for dry soil.

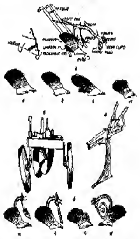

FIG. 18. — The plow. (1), modern walking plow with parts named; (2), types of moldboard for (a) stubble ground, light soil, (b) fallow ground, clay soil, (c) sod ground, (d) general purpose, fairly well suited to a wide range of soil conditions. (3), deep-tilling disk plow; (4), subsoiler; (5), plow attachments: (a) jointer, (b) knife or beam colter, (c) fin colter, (d) rolling colter.

572. **Shapes of moldboard plows.** — Of the moldboard type there are two general shapes: (1) The long, sloping moldboard, which rises very gradually and has little or

no overhang, found on what is called the sod plow. This neatly cuts off the roots at the bottom of the slice, slowly and gradually twists the soil over without breaking the sod, and lays it smoothly up to the previous furrow slice. (2) The short, steep moldboard with a marked overhang. This is not adapted to sod land, because it breaks up the sod and shoots it over in a rough, jagged manner with uneven turning. But on fallow land, to which it is adapted, it very completely breaks up the soil and throws it over in a nearly level, mellow mass. The pulverizing effect is obviously much greater than with the sod plow. Since the steep moldboard, or fallow-ground, plow exerts the most force on the soil in a given time at a given speed of movement, it follows that if a particular soil is over-wet it should be plowed with the sod plow; while, if it must be plowed when too dry, the fallow-ground plow will be more effective disregarding the draft, which will probably be larger in the latter case.

573. Position of the furrow slice (Fig. 60).—Considerable care should be taken concerning the angle at which the furrow slice is placed. It is seldom desirable to completely invert the soil. If it is too flat, the stubble and rubbish are matted at the bottom of the furrow and tend to interfere with capillary movement for a considerable period. This may cause serious difficulty on spring-plowed soil, where the capillary connection does not have time to be renewed before a crop occupies the land. If, on the other hand, the furrow is too steep, the proper pulverization does not take place and the turning under of stubble and rubbish is not satisfactorily accomplished. The stubble and rubbish are likely to interfere with subsequent operations.

The best angle at which to turn the furrow slice is

about from 30° to 40° with the horizontal. A furrow thus set furnishes ready entrance for rain water and facilitates the best of aëration for the soil. Such an angle is especially to be recommended for turning under green manures. The capillary connections with the subsoil are not broken and the green material is well distributed from the top to the bottom of the furrow. Where a sod is to be plowed, a flatter turning of the furrow is advocated in order to increase the packing and avoid the danger of the sod's interfering with subsequent cultivation.

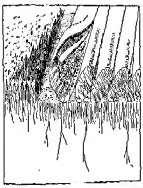

Fig. [illegible]. – Section of plowed land showing the normal proportions and position of the furrow slice as left by a moldboard plow. The effect of the jointer in turning under the edge of the furrow slice as well as the position of turned under vegetation is apparent.

574. Depth and width of furrow. – There is a general relation between the width of the furrow slice and its depth. In general, it may be said that this ratio is about

two in width to one in depth. The greater the depth, the less in proportion may be the width of the furrow slice.

On clay soil in particular, there is also a relation between depth and condition. A wet soil should be plowed more shallow, other things being equal, than a dry soil, because the puddling action is less. On a dry soil the depth should be increased, in order to increase the pulverization. Combining these principles, then, it may be said that if a clay soil must be plowed when too wet, it should be plowed with a sod plow and to as shallow a depth as is permissible. But on an over-dry soil the opposite conditions should be fulfilled — that is, the use of a steep moldboard and to an increased depth. Likewise, on sandy soil, where the aim is generally to compact the structure, this may be furthered by deep plowing with a steep moldboard when the land is over-wet.

575. Plow sole. — In connection with this phase of the subject it is important to consider what is often called the "plow sole," — that is, the soil at the bottom of the furrow, which bears the weight of the plow and the trampling of the team, and which under a uniform depth of plowing does not become loosened. In clay soil, especially, it gradually becomes more compact, developing in time something of a hardpan character, which is detrimental to the circulation of air and moisture and interferes with the penetration of plant roots. Consequently, occasional deep plowing, or even subsoiling, is recommended to break up this unfavorable soil structure. There is less tendency for the disk plow than for the moldboard plow to form the "sole."

576. Hillside plow. — The hillside plow is a modified form of the moldboard plow. It has a double curvature to the moldboard, so that it is essentially two plows in

ous. The plow swings on a swivel in such a way that it may be locked on either the right or the left side. It removes the necessity of plowing in beds, and, by permitting all the work to be done from one side, enables the plowman to lay the furrow slice in one direction. On the hillside this direction is down the slope, because of the greater ease in turning the soil in that direction. This plow also removes the difficulty of pulling up and down the hill. There is another type of moldboard plow, designed to eliminate "dead furrows" and "back furrows." Dead furrows are developed by the last furrow slices of two lands being turned in opposite directions, thereby leaving a gulley between, which is often unproductive in character; the back furrow consists of two furrow slices thrown together, usually forming a ridge more productive than the average of the land. This plow is of the sulky type, the plow being carried on wheels and regulated by means of levers and the traction power. Two plows are carried, one having a right-hand turn to the moldboard, and the other a left-hand turn. By using one plow in one direction and the other in the opposite direction, it is possible to begin on one side of the field and throw the furrow slice in one direction until the entire area is covered, thereby leaving the soil in a uniform condition. Such plows, being heavier than the single, walking plow, are not adapted to very uneven ground.

577. **Covering rubbish.** — The secondary function of the plow is to cover weeds, manure, and rubbish that may be on the surface. This also the turning plow does very effectively. The cutting and turning of the sod, rubbish, and weeds is facilitated by several attachments, such as colters, jointers, and drag chains. There

are several types of colters. Blade colters are attached to the beam or to the share in such a manner as to cut the furrow slice free from the land side. They should be adjusted in such a position as to cut the soil after it has been raised and put in a stretched condition, at which time the roots are most easily severed. This position is a little back of the point of the share. A knife edge attached to the share is commonly called a fin colter. A jointer is a miniature moldboard attached to the beam for cutting and turning under the upper edge of the furrow slice, so that a neat, clean turn is effected without the exposure of a ragged edge of grass which may continue growth. This is used chiefly on sod land. A drag chain is an ordinary heavy log chain, one end of which is attached to the central part of the beam and the other to the end of the double tree on the furrow side, and with enough slack so that it drags down the vegetation on the furrow slice just ahead of the turning point. It is used primarily in turning under heavy growths of weeds or green-manure crops.

478. **Subsoil plow.**—There is a third type of plow, the so-called subsoil plow. The purpose of this implement is to break up and loosen the subsoil without mixing the material with the soil. It consists essentially of a small, molelike point on a long shin. This implement is drawn through the bottom of the furrow, and shatters and loosens the subsoil to a depth of 18 inches or 2 feet. It is often useful on soils having a dense, hard subsoil. Its use requires the exercise of judgment, as the process may prove very injurious if done out of season. As a general rule, it is best to use the subsoil plow in the fall, when the subsoil is fairly dry and may in a measure be recompacted by the winter rain. Spring subsoiling is

seldom advisable in humid regions, owing to the danger of puddling the subsoil, or to the possibility of its remaining too loose for best root development if the work is done when the subsoil is dry enough not to puddle.

579. Cultivators (Fig. 70). — There are more types of cultivators than of any other form of soil-working implements. These may be grouped into (1) cultivators proper; (2) leveler and harrow types of cultivators; (3) seeder cultivators. These implements agree in their mode of action on the soil, in that they lift up and move it sidewise with a stirring action which loosens the structure and cuts off weeds, and to a slight degree covers rubbish. However, the action is primarily a stirring one, and, in general, it is much shallower than that of the plow. One important fact should be kept in mind in cultural operations, especially those just following the plowing; that is, the work should be done when the soil is in the right moisture condition. Particularly is this true in the pulverization following the plowing. Plowing, if it is properly done, leaves the soil in the best possible condition to be further pulverized. It is properly moistened, and if the clods are not shattered they are reasonably frail and may be much more readily broken down than when they are permitted to dry out. In drying they are somewhat cemented together and thereby hardened. Not only is it desirable in almost all cases to take advantage of this condition of the soil, but the leveling and pulverizing of the soil reduces drying and improves the character of the seed bed.

580. Cultivators proper. — There is a great variety in types and patterns of cultivators. They may be divided into large shovel forms and small shovel forms, and the duck-foot form. The first type has a few com-

paratively large shovels set rather far apart, which vigorously tear up the earth to a considerable depth and leave it in large ridges. There is a lack of uniform action, and the bottom of the cultivated part is left in hard ridges. Such implements are now much less used than they were formerly, and may be considered to supplant in a measure the use of the plow, where deep working without turning

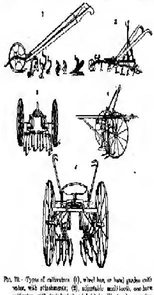

FIG. 111.—Types of cultivators. (1), wheel hoe, or hand garden cultivator, with attachments; (2), adjustable small-tooth, one-horse cultivator, with duck-foot shovel behind; (3), two-horse spring-toothed cultivator; (4), two-horse sweep or knife cultivator; (5), two-horse disk cultivator.

is desired. Some of the wheel hoes used in orchard tillage belong to this type. The single and double shovel plows are earlier types of the same implement.

The small shovel cultivators have very generally supplanted the large shovel type in most cultural work. The decrease in size of shovels is made up by the great increase in number. Ordinarily they operate to shallow depths, but very thoroughly and uniformly. They are now much preferred in all intertillage work for eradication of small weeds and the formation of a loose surface mulch.

The duck-foot cultivator — or sweep as it is called in the southern states, where it is extensively used in the cultivation of cotton — is a broad blade that operates in a nearly horizontal position an inch or two beneath the surface. The surface layer of soil is severed and raised slightly from the under soil, and is somewhat crumbled in the operation. This tool is very efficient in establishing and maintaining a mulch and in destroying weeds. It covers every part of the soil. The implement is increasing in popularity in the northern and eastern states. It is not adapted for use in very stony or hard soil.

Another classification, which has less relation to utility than to the convenience and comfort of the operation, is based on the presence or the absence of wheels. There is a strong movement toward the use of wheel cultivators carrying a seat for the operator. These have a wider range of operation as to depth and facility of movement than have the cultivators without wheels.

Still further, there is the distinction of shovels from disks. Disks are used on the larger cultivators but seldom on the small ones.

Cultivators may be constructed to till one or more rows at a time.

681. Leveler and harrow types of cultivator (Fig. 71). — In this group are the spike-tooth harrow, the smoothing harrow, the spring-tooth harrow, the disk harrow, the spading harrow, weeders, and the Acme and Meeker harrows.

The spike-tooth harrow is essentially a leveling implement, adapted to very shallow cultivation of loose soils. It is also something of a cleaner, in that it picks up surface rubbish. The spring-tooth harrow works more deeply than does the spike-tooth harrow, and can therefore be used in many soils for which the latter is not adapted. In working down cloddy soil it brings the lumps to the surface, where they may be crushed. The disk harrow depends for its primary advantage on the conversion of sliding friction into rolling friction. Its draft is therefore less for the same amount of work done. It has a vigorous pulverizing action similar to that of the plow, surpassing shovel cultivators in this respect. The disk harrow is not adapted to stony soil, but the toothed forms are as effective on such soil as on soil free from stones, as long as the stones are not large enough to collect in the implement. On the other hand, on land full of coarse manure, sod, and the like, the disk harrow is the more efficient. The spading harrow (cutaway disk) is very little different from the disk harrow, except that it takes hold of the soil more readily. A recent attempt to bring about a high degree of pulverization, and with greater uniformity, is represented by the double-disk implements. In these implements there are two sets of disks, one set in front of and zigzagged with the other, and the two adjusted so as to throw the soil in opposite directions.

Weeders are a modified form of the spring-tooth harrow, adapted to shallow tillage of friable, easily worked

soil, where the aim is to kill weeds and create a thin surface mulch. They are wide and are fitted with handles, and therefore have an intermediate place between cultivators proper and harrows. They are much used for intertillage of young crops.

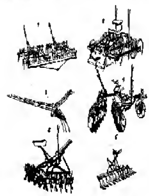

FIG. 71.—Types of harrows: (1), spike-tooth; (2), spring-tooth; (3), weeder; (4), double disk (note that the forward disks are solid while the rear disks are of the cut-out type); (5), spading disk; (6), Acme. All these belong to the cultivator group of implements.

The Acme harrow consists of a series of twisted blades which cut the soil and work it over. They are most useful in the later stages of pulverization on soil relatively free from stones. The Meeker harrow is a modified form of disk, used primarily for pulverization. It consists of a series of lines of small disks arranged on straight axles, and is especially adapted to breaking up hard, lumpy soil.

In this particular it may be considered as belonging to the third set of implements, the clod crushers. But as compared with the roller on hard soil it is more efficient.

582. Seeder cultivators. — Many implements used primarily for seeding purposes are also cultivators, and their use is equivalent to cultivation. The grain drill is a good example of this group. It is essentially a cultivator — either shoe or disk — adapted to depositing the grain in the soil at the proper depth. All types of planters that deposit the grain in the soil have a similar action on the structure of the soil. The ordinary two-row maize planter, the potato planter, and the like, while of low efficiency as cultivators, still have an effect which is measurable. This action is well seen in the lister, used for planting maize, by which the grain is deposited beneath the furrow, which is filled by cultivation after the grain is up. The lister is generally used without previously plowing the ground, and its use is limited to regions of low rainfall where the soil is aërated by natural processes. Plowed ground listers have lately been introduced, which combine the advantages of deep planting with proper preparation of the soil.

There is also a very considerable tillage action in many harvesting implements. The potato digger, for example, very thoroughly breaks up and cultivates the soil, and this process is one important reason for the general high yield of crops following the potato crop. Bean harvesters and beet looseners also have a similar action on the soil.

583. Packers and crushers. — These may be divided into two groups — those implements that aim to compact the soil, and those the primary purpose of which is to pulverize the soil by crushing the lumps. Both kinds

of implements have something of the same action on the soil. That is to say, any implement that compacts the soil does a certain amount of crushing; and, conversely, any implement that crushes the soil does some compacting.

686. Rollers (Fig. 73). — The type of the first group is the solid, or barrel, roller, which by its weight tends to force the particles of soil nearer together and to smooth the surface. The smaller the diameter in proportion to its weight, the greater is the effectiveness of the roller. Its draft is correspondingly greater. As a crusher, the roller is relatively inefficient on hard, lumpy soil, because of its large bearing surface. Lumps are pushed into the soft earth rather than crushed.

It should be mentioned that there is one condition under which the roller is effective in loosening up the soil structure. This is on fine soil on which a crust has developed as a result of light rainfall. Here the roller may break up the crust and restore a fairly effective soil mulch.

Another form of roller is the subsurface packer. One type of this implement consists of a series of wheels with narrow, V-shaped rims, which press into the soil and compact it while leaving the surface loose. The wheels are designed primarily to smooth the land after plowing, and to bring the furrow slices close together and in good contact with the subsoil, in order to conserve moisture and promote decay of organic material that may be plowed under. This packer has been developed chiefly in semi-arid and arid sections of country where the conservation of moisture is especially important, but it might well have a much larger use for the same purpose in sections of the country that are subject to late summer and fall

droughts. While compacting the soil, this implement leaves a mulch.

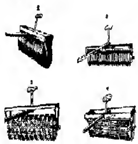

Fig. 73.—Types of packers and pulverizers: (1), solid or barrel roller; (2), corrugated roller; (3), crusher and subsurface packer; (4), bar roller.

586. Clod crushers. The aim of these clod crushers is to break up lumps. As to mode of action, there are several forms. The corrugated and the bar roller and the clod crusher concentrate their weight at a few points, and are open enough so that the fine earth is forced up between the bearing surfaces. They are very effective in reducing lumpy soil to comparatively fine tilth. They have very little leveling effect further than the breaking down of lumps.

The planker, drag, or float, variously so-called, consists essentially of a broad, heavy weight without teeth, which is dragged over the soil. The lumps are rolled under its edge and ground together in a manner which very effectively reduces their size. At the same time the soil is leveled, smoothed, and, to a degree, compacted. This implement may well be used in the place of the roller

as a pulverizer, on many occasions. It is constructed in many forms.

586. **Efficient tillage.** – Efficient tillage requires an understanding of the properties of the soil, good practical judgment as to its condition, facility in the selection of the proper implements for its modification, and mechanical skill in their operation. The same result may often be attained in different ways, and the practical necessity that frequently arises for the farmer to get on with a relatively few tillage implements where a variety of soil conditions must be dealt with draws heavily on his resourcefulness.

CHAPTER XXX

IRRIGATION AND DRY-FARMING

IRRIGATION [1] is the application of water to the soil for the purpose of growing crops. It is supplementary to the natural precipitation. The quantity of water applied and the time of application must therefore be determined by the character of the rainfall.

587. **Relation of irrigation to rainfall.** — The limit of rainfall where irrigation becomes necessary is not a fixed

[1] Widtsoe, J. A. Principles of Irrigation Practice. New York. 1914.

Olin, W. H. American Irrigation Farming. Chicago. 1913.

Bowie, A. Practical Irrigation. New York. 1908.

King, F. H. Irrigation and Drainage. New York. 1899.

Paddock, W., and Whipple, O. B. Fruit Growing in Arid Regions. New York. 1910.

Newell, F. H. Irrigation. New York. 1902.

Mead, E. Irrigation Institutions. New York. 1903.

Mead, E. Preparing Land for Irrigation and Methods of Applying Water. U. S. D. A., Office Exp. Sta., Bul. No. 145. 1904.

Wickson, J. A. Irrigation among Fruit Growers on the Pacific Coast. U. S. D. A., Office Exp. Sta., Bul. No. 108. 1902.

Widtsoe, J. A., and Merrill, L. A. Methods for Increasing the Crop Producing Power of Irrigation Water. Utah Agr. Exp. Sta., Bul. No. 118. 1912.

Fortier, S. The Use of Small Water Supplies for Irrigation. U. S. D. A., Yearbook, p. 409. 1907.

Fortier, S. Irrigation of Orchards. U. S. D. A., Farmers' Bul. 404. 1910.

amount. Irrigation is practiced in all parts of the world — in those regions where the rainfall is 50 and 60 inches a year, as well as in those regions where it is only 20 inches or less. (See Fig. 73.) The need of irrigation is determined by (1) the time when the rainfall occurs, (2) the way in which it occurs, whether in small or

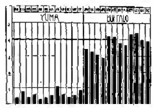

FIG. 73.—Diagram showing the extent and distribution of rainfall in an arid region (Yuma, Arizona), and a humid region (Buffalo, New York).

large quantities, (3) the nature of the soil, (4) the air temperature and wind movement, and (5) the nature and value of the crops grown. Other factors, such as the cost of applying water, methods of tillage, and market facilities, have some influence in determining the practicability of irrigation. Irrigation is usually associated with a low rainfall of 20 or 25 inches a year. Using these figures as a measure of the need of irrigation throughout the world, it appears that about 60 per cent of the earth's surface has so low a rainfall that irrigation is necessary in order to secure paying yields of crops. About 25 per cent of the earth's surface receives 10 inches or less of rainfall annually. About 30 per cent receives between 10 and 20 inches, and about 10 per cent

receives between 20 and 30 inches. Every continental area has its arid portion where the rainfall drops below 10 inches. (See Fig. 75.) These sections are usually in the interior, but their position depends on the topography of the land and the direction of the moisture-laden winds. Sometimes, as in the western United States, the coastal mountains cause an arid climate in the adjacent interior valleys, some of which extend quite out to the ocean as in southern California.

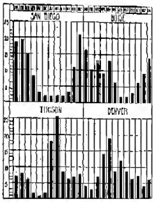

FIG. 74.—Four types of rainfall. The diagrams show the distribution by months.

It has been estimated that the total available water supply is sufficient to irrigate only one-tenth to one-fifth of the proportion of the earth's surface in need of such treatment.

588. Extent of irrigated land.—In 1905, Mead[1] estimated the total area of land irrigated at 100,000,000 acres. Since that date the practice of irrigation has been extended rapidly in all parts of the world, and it is probable that at the present time the total area of land irrigated is at least 200,000,000 acres. In Egypt, in Australia, and in India, as well as in the United States, large projects for irrigation developments have recently been undertaken. In the United States, according to the Thirteenth Census, the area of land irrigated increased 7,500,000 acres between 1899 and 1909. At the latter date enterprises for the provision of water were under way to cover a total of 31,000,000 acres.

589. History of irrigation.—The practice of irrigation is very ancient. The very earliest records of the peoples in the valleys of the Nile and Euphrates rivers, in Africa and Asia, mention large irrigation works. In China and India also the practice is very old. The remains of ancient works for irrigation often amaze the modern engineer by their size and excellence of construction, considering the facilities that were available. As early as 2084 B.C. an artificial lake fifty miles in circumference was constructed in Egypt, communicating with the Nile through a canal. The Great Imperial Canal in China, connecting the Hoangho River with the Yangtse, was 650 miles long and had several lakes in its course. In Peru, Mexico, and the southwestern United States, there exist remains of very extensive irrigation works of great antiquity. In Argentina large irrigation canals may still be traced for from four to five hundred

[1] Mead, E. Irrigation Engineering and Practice. American Cyclopedia of Agriculture, p. 420. New York. 1907.

miles. In the Verde River valley in Arizona, remains of the cliff dwellings, which were scattered long before the advent of the Spanish explorers, are associated with extensive irrigation canals showing much skill. The ditches and the reservoirs were finished with hard linings of tamped or burned clay, and in one instance a main canal was cut for a considerable distance in solid rock. Sometimes a smaller ditch was sunk in the bottom of a large canal, to facilitate the movement of small runs of water. The ancient canals in the Salt River valley[1] had a length of at least 150 miles and were sufficient to irrigate 250,000 acres of land.

In modern times the great Assouan dam has been built on the Nile River, and with the associated reservoirs it is designed to control the flow of the river and provide water for irrigation. It stands as an example of present-day irrigation development and control.

890. Development of irrigation practice in the United States. — In the United States the earliest modern people to practice irrigation were the Catholic missionaries in southern California. The immediate predecessors of the present irrigation systems in the United States were built by a colony of one hundred and forty-seven Mormons who went into the Salt Lake valley in Utah in July, 1847. The crops of these people were grown with water diverted from City Creek, and their community life, together with their peculiar situation, led them to work out in the succeeding decades the fundamental principles of economic and social life as adapted to irrigation farming. In the last thirty years the practice of irrigation has

[1] Forbes, R. H. Irrigation in Arizona. U. S. D. A., Office Exp. Sta., Bul. No. 235, p. 9. 1911.

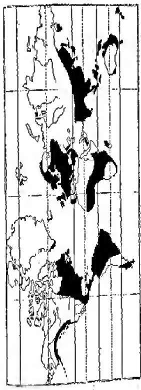

FIG. 70.—Map showing the distribution of rainfall in the world. Arid and semiarid regions in white. Humid regions in black.

extended rapidly in the western United States. It has approximately doubled each ten years since 1879.

Irrigation is employed somewhat generally throughout the region west of the 100th meridian, which runs through central Nebraska. With the exception of limited areas the annual rainfall is less than 25 inches, and over large areas it is less than 15 inches.

The methods of securing water and applying it to the land have grown up gradually out of the experience of the people in many communities and under many conditions. Coöperative effort of some sort is essential to provide water for irrigation, and this has led to the use of several types of organizations for the purpose. Naturally, the states concerned have taken a part in the matter by passing laws and providing funds to promote irrigation practices. Finally, the aid of the Federal Government was enlisted. The enterprises for the provision of water for irrigation may be divided into seven groups,[1] chiefly according to their legal status: (1) commercial enterprises selling water for profit; (2) partnerships among individual farmers without formal organization; (3) coöperative enterprises, made up of water users; (4) irrigation districts which are public corporations; (5) Carey Act[2] enterprises, by Federal enactment authorized August 18, 1894, and made up of grants to the arid and semiarid states, these states being held responsible for the irrigation of these grants; (6) United States Indian Service enterprises, to provide for the construction of irrigation works in Indian reservations; and (7) the United States Reclamation Serv-

[1] Thirteenth U. S. Census, Chapter 14, p. 421. 1910.

[2] Stover, A. P. Irrigation under the Carey Act. U. S. D. A., Office Exp. Sta., Ann. Rept. pp. 451–488. 1910.

ice, established by Federal law June 17, 1902, providing for the construction of irrigation works with the receipts from the sale of public lands in the arid and semi-arid states.

These several provisions and their successive growth in size suggest the necessity of large enterprises and careful coördination in providing water for irrigation. The many attractive features of farming in arid regions under irrigation, together with the publicity that the enterprises have had, have hastened the growth of irrigation farming so that it now plays a very substantial part in the agricultural business of the country.

591. Irrigation in humid regions. — In the humid states — that is, those in which there is a large normal rainfall and in which crops can usually be produced without artificial addition of water — irrigation has been practiced to some extent. Irrigation is used (1) where the crop has a high value, as for vegetables and small fruits near large cities; (2) where the quality of the crop is much affected by unfavorable conditions, as the production of wrapper tobacco in northern Florida and of rice in Louisiana; (3) where the soil is especially sandy; and (4) where the supply of water may be very cheaply applied to the land, as in the diversion of streams to adjacent fields, usually meadows. In Great Britain and in central and southern Europe, the diversions of streams to near-by grass meadows is relatively common. Under all these conditions, small irrigation enterprises have been developed in different parts of the eastern United States. The rainfall under which irrigation is practiced in these regions ranges from 30 to more than 60 inches annually. The practice of irrigation in humid regions is in the nature of an insurance against dry years. The

probability of the occurrence of these in the eastern United States is shown in the following table[1] of rainfall records for the ten years from 1900 to 1909, inclusive:—

Station	Average Annual Rainfall	Number of Fifteen-day Periods or over with less than 1 inch of Rain	Number of Days when Irrigation was Required (a)
Ames, Iowa	30.39	23	100
Oshkosh, Wisconsin . . .	29.78	27	392
Vineland, New Jersey . . .	47.47	46	352
Columbia, South Carolina .	47.55	62	508
Selma, Alabama	50.75	60	724

(a) No days counted until after a fifteen-day period with less than 1 inch of rain.

The aggregate area of the projects is small and amounts to only a few thousand acres.

592. The Reclamation Service. — The financing of irrigation enterprises by the Federal Government through the Reclamation Service has been a wonderful stimulus. The total number of acres on which ditches have been constructed or are in process of construction in this way aggregates 3,101,450, in thirty projects distributed through seventeen states and involving a total expenditure of hundreds of thousands of dollars. These projects contemplate the impounding of 13,272,490 acre-feet of water.

[1] Williams, M. B. Possibilities and Need of Supplemental Irrigation in the Humid Regions. U. S. D. A., Yearbook 1911, pp. 309–320.

Also, Teele, R. P. Irrigation in Humid Regions. American Cyclopedia of Agriculture, p. 437. New York, 1908.

About one-third of this area was irrigated in 1915. Many of the dams and canals involved are of stupendous size and necessitate feats of bold engineering. Often hydro-electric power is developed in large amount in the passage of the water from the reservoirs to the fields where it is to be used to grow crops.

693. Legal, economic, and social effects of irrigation. — The practice of irrigation on an extensive scale has caused important changes in the construction of law[1] relative to water and property rights and in commercial and social organization.

Riparian rights in streams and lakes under humid conditions, for purposes of domestic use, power, and transportation, must be modified in an arid country. Here values of all real property depend largely on the supply of water for purposes of irrigation. The control and use of water becomes of the utmost public concern. Consequently the use of water for the purpose of growing crops takes precedence over use for all other purposes except domestic use. In nearly every country in the world where irrigation is extensively practiced, the state or the government has assumed ownership or a large measure of control over the water in all lakes and streams. The necessity of the use of water for irrigation has conferred

[1] Mead, E. Irrigation Institutions. New York, 1903.

Mead, E. Irrigation Institutions in Different Countries. American Cyclopedia of Agriculture, Vol. IV, p. 154. New York, 1909.

Hess, R. H. Further Discussion of American Irrigation Policies. American Cyclopedia of Agriculture, Vol. IV, p. 160. New York, 1909.

Hess, R. H. Socio-Economic Aspects of Irrigation. American Cyclopedia of Agriculture, Vol. IV, p. 167. New York, 1909.

certain privileges, such as the principle of eminent domain, in conserving and utilizing water. The provisions differ somewhat in detail, but in general agree in conferring the right to use water upon those persons who can first make the best use of it for the purpose of growing crops. Other rights in the use of water are largely subject to its use for irrigation. Further, the tendency is to attach the right to the use of water to the title to land, since each has value only as it is associated with the other. However, in the attachment of water from a particular source to any given area of land, many difficult questions may be raised which must be decided by the larger principle of beneficial use.

A close economic dependence among the people and a high degree of social coördination grows out of the practice of irrigation farming on a large scale. The fertile nature of the soil, the favorable climate, and the coöperation necessary to supply water for irrigation, leads to intensive methods of farming, to specialization in production, and to many coöperative enterprises, not only in agriculture, but also in associated industries in the same region. These intensive practices and the close personal association involved promote a high intellectual and social standard in the community. Irrigation has been an efficient schoolmaster in the practice and value of coöperation in all sorts of enterprises.

594. Divisions of irrigation. — Two main parts make up the practice of irrigation: the first is the provision of water, which is essentially an engineering problem;[1] the second is the use of water on the land, which is es-

[1] Wilson, H. M. Irrigation Engineering, p. 525. New York, 1909.

sentially an agricultural problem. It is important to maintain this clear distinction in dealing with the practice of irrigation, especially in its larger aspects. The two functions are largely exercised by different groups of men, and they involve widely different types of knowledge and skill. The supreme test of an irrigation system is efficient use of the water on the land in the production of crops.

595. Sources of water for irrigation. — The practice of irrigation is dependent on some adjacent supply of water that may be diverted on to the land. It may be derived by (1) the diversion of streams flowing from well-watered regions; (2) the melting of snow on mountain areas; (3) the regulation of the flow of streams by storage reservoirs; and (4) the utilization of underground water by means of wells. All these sources may require the construction of large and costly works, which are well exemplified in the structures built by the United States Reclamation Service and by the Egyptian government in the Nile valley. Dams hundreds of feet high and thousands of feet long, containing millions of cubic yards of masonry and concrete, have been constructed for these purposes.

596. Canals. — The conveyance of the water from the point of supply to the place where it is to be used necessitates further difficult engineering problems, which in some cases have entailed the construction of large tunnels under mountains and the development of large pumping and power plants as well as the construction of thousands of miles of main and lateral canals. In 1909 the length of main irrigation ditches in the United States was 875,911 miles, and of laterals 38,062 miles. As a rule the water is conveyed by gravity flow without pressure. Important

problems presented relate to the prevention of seepage, erosion, and evaporation. The loss[1] of water in transit from its source to the field has been found to average 60 per cent, and to range from 0.25 per cent to as much as 64 per cent a mile with an average of about 6 per cent. The seepage water from canals may result in further loss by accumulating in low lands, where the evaporation, coupled with the solution of the soluble salts in the soil, causes injurious accumulation of alkali in the surface soil, and in extreme cases a swampy condition which destroys the value of the soil for agricultural purposes. In order to prevent seepage many kinds of lining and treatment of the walls of canals have been employed. Cement lining in different forms, wooden flumes, clay puddling, oiling, applications of tar, and silting have been used. The need of a lining depends much on the nature of the formation through which the ditch passes. Silt is an excellent means of checking seepage. Where clear water is carried, the ditch must usually be lined, and the practice of lining canals in order to reduce seepage is increasing rapidly. Sand and gravel permit much seepage and are easily eroded. Clay permits little seepage and is not easily eroded. The velocity of flow of water in canals should not exceed three feet a second. In large canals this will not permit a grade of more than six inches in a mile; in very small ditches a grade of from forty to fifty feet in a mile may be necessary to cause the same velocity of flow. A lining that is not subject to erosion, together

[1] Teel, R. P. Irrigation and Drainage Investigations. U. S. D. A., Office of Exp. Sta., Ann. Rept. 1904, p. 36. Also Mead, E., and Etcheverry, B. A. Lining of Ditches and Reservoirs to Prevent Seepage Losses. Calif. Agr. Exp. Sta., Bul. No. 188. 1907.

with a channel that is deep in relation to its width, not only reduces seepage, but also, by permitting the rapid flow of water, reduces loss by evaporation.

At the farm on which the water is to be used, it is distributed in small field laterals which are carried on the higher ground. Precautions against seepage and evaporation should here be taken. The tendency now is toward the distribution of the water to the fields by means of underground pipes, with standpipes and valves at the points of discharge. The arrangement of the farm laterals must of course be determined by the topography of the land, since the water flows by gravity.

597. **Preparation of land for irrigation.** — The preparation of the land for irrigation depends on the method used to apply the water. Usually marked irregularities should be removed by smoothing the surface. When any sort of basin method of irrigation is used, it may also be necessary to level the surface. Various types of scrapers and levelers have been found useful for this operation. Much of the arid and semiarid land carries a growth of sage brush or other bushy vegetation, and of course this must be removed before smoothing operations can become effective.

598. **Methods of applying water.** — There are four general methods[1] of applying water to the soil. These are (1) overhead sprays, (2) sub-irrigation, (3) flooding, and (4) furrows.

599. **Overhead sprays.** — By the overhead spray system (Fig. 76) the water is distributed in pipes under a pressure of forty to sixty pounds and discharged from a series

[1] Fortier, S. Methods of Applying Water to Crops. U. S. D. A., Yearbook 1909, pp. 293-308.

of nozzles. Several types of nozzles are employed. The amount of water that can be applied is relatively small, and consequently the method is used chiefly in humid regions to supplement a rather high rainfall, in the growth of crops of large value. It is used in the growth of truck and small fruit crops near the large eastern cities.

The advantages of the system are: —

1. The water is conveniently applied at the desired point. 2. The system may be used on uneven land and without preparation of the surface. 3. There is no waste of land by ditches. 4. The application of the water is easily controlled by valves and by the movement of the pipes.

The disadvantages of the system are: —

1. The capacity is limited. 2. The cost is high for equipping and maintaining the plant, and for developing the pressure requisite to suitably distribute the water from the nozzles. 3. There is possibility of injury to crops where water is applied on warm, bright days, since the water comes into contact with the foliage.

600. Sub-irrigation. — Sub-irrigation is the distribution of water from underground pipes. These are buried in the soil and perforated in such a way that the water finds an outlet and is distributed by the capillarity of the soil and by natural gravity flow. In greenhouses and where shallow-rooted annuals are grown, lines of drain tile are employed, the water flowing out at the joints. Continuous pipes having an open seam or perforations have been used. Another method employs a porous cement plug which rises a little above the supply pipe. The object of the last-named method is to avoid the common difficulty from the entrance of roots into the pipes. The pipes must have a very slight grade in order to insure a

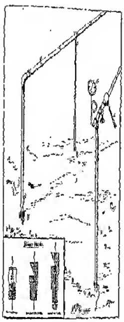

Fig. [illegible].—Essential features of construction in one method of overhead spray irrigation. Water is supplied under pressure from underground pipes and is distributed from small nozzles (N) along the side of the pipe. Different forms of nozzles are used for different purposes (see detail). Gauge (G) shows pressure, (S) is pipe support, and (L) is lever for turning the discharge pipe, which is fitted with a [illegible] joint.

uniform distribution of water. They operate under little or no pressure. The system has a number of advantages, but in practice these are usually more than offset by its disadvantages. The advantages are: —

1. The system is permanent. 2. It is economical of water. 3. There is no injury to the physical properties of the soil. 4. There are no obstructions at the surface. 5. The deep rooting of crops is encouraged. 6. There is very little expense for supervision of the distribution of water. 7. The accumulation of soluble salts on the surface of the soil by evaporation is reduced. 8. The system may sometimes be used as a means of drainage also.

The disadvantages are: —

1. There is a strong tendency for the pipes to be clogged by the entrance of roots, especially where perennial crops are grown. The porous-plug method of discharging water is designed to reduce this difficulty. 2. The slow lateral capillary diffusion of water in dry soil makes it necessary to install the lines of pipe near together, which entails heavy expense.

The method is best adapted to shallow-rooted annual crops, and least adapted to orchards. The seepage of water from the pipes attracts the growing roots, which are likely to enter the pipes, break up into many small fibers, and clog the system.

There are soil conditions under which this method is especially useful. Where the soil is a porous sand or gravel underlaid at a depth of four feet or less by a rather impervious stratum, the water may be distributed rapidly from the pipes so that it accumulates on the hard substratum and saturates the soil, the pipes being quickly emptied. There is then no tendency for the roots to enter the pipes, and the porous nature of the soil permits

the pipes to be placed several rods apart, thus reducing the expense of installation.

Sub-irrigation sometimes occurs naturally under conditions similar to those just described, where water is supplied from springs or by seepage. Where it can be employed, sub-irrigation is the ideal method of applying water to the soil.

601. Methods most used in arid regions. — The two methods preëminently used to apply water to the soil under arid conditions are by furrows and by flooding. The land must generally be prepared to some extent for either of these methods, by smoothing or leveling the surface, throwing up levees, or constructing distribution furrows. It is a fortunate fact that the subsoil in arid regions is about as fertile as the soil, and therefore grading can be practiced with impunity. Both methods have a large number of variations in detail to adapt them to particular soils, topography, or crops.

The chief factors determining the choice between flooding and furrowing are (1) the nature of the crop, (2) the character of the soil, (3) the contour of the land, and (4) the quantity of water available.

602. Flooding. — Flooding is especially employed (1) where the crop occupies the entire area, such as in grainfields and meadows, (2) where the soil is of medium porosity and does not bake seriously on drying, (3) where the surface is relatively flat; and (4) where the supply of water is relatively large.

The advantages of this method are: —

1. The handling of water is easy.
2. There is economy in ditches.
3. The necessity of tearing up the crop is avoided.
4. The method is especially suited to certain crops

that grow in standing water, such as rice and cranberries.

Its disadvantages are: —

1. A large quantity of water is required.

2. Over irrigation, with consequent seepage and difficulties from alkali, is likely to occur.

3. On heavy soil, puddling and checking of the surface soil result from lack of tillage.

4. Some crops are injured by direct contact with water.

5. The cost of leveling and of construction of levees is large.

There are two main types of flooding. In the first the water is turned into level checks or blocks, where it stands until it is absorbed by the soil — called commonly closed-field flooding. In the second type the water is distributed in a moving sheet or a series of small rills, from field supply ditches — called open-field flooding. This method is used only where there is a moderate slope to carry the water.

In closed-field, or check, flooding, the land is divided into blocks, each having a level surface and surrounded by a levee. The size of the checks, their shape, and the height of the levees is determined by the contour of the land. On a slope they may be very irregular. Small checks of one to three acres are most successfully irrigated, but areas of twenty or more acres have been flooded in one block. A flow of five to seven second-feet of water is necessary in order to make the method thoroughly successful. One man can irrigate from five to twenty acres a day, depending on the size and form of the checks. The levees may be permanent, as is usually the case especially in meadows, or they may be thrown up for each application of water. The permanent levees may

be broad and low so that they will not interfere with harvesting. This method of flooding is falling into disuse.

A phase of check flooding is the basin method of irrigating orchards, in which small, shallow basins are formed around each tree and separated from the trunk by a block

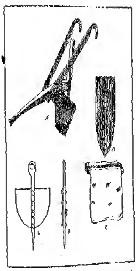

FIG. 72. Implements used in irrigation practice. (A), scraper for making small levees in irrigation furrows; (B), (C), and (D), wood and metal tappoons used in close irrigation furrows and by means of the small openings divide and regulate the flow. (E), canvas dam used in flooding from field ditches. The edge of the canvas is held down by a shovelful of earth.

of earth to prevent injury to the growing wood. This method is used rather extensively throughout the arid regions.

In the open-field, or blind, flooding, the water is supplied in ditches which are carried across the contours at a moderate grade, and at intervals the flow is intercepted by a canvas dam or other obstruction and forced to flow over the lower bank, from which point it is distributed down the slope and over the field in numerous small trenches. Any surplus water is collected in a ditch at the lower side of the field. In this method of applying water constant attention is required to guide the flow and prevent erosion. One man can irrigate from five to ten acres in a day. This method is used in irrigating grainfields and sloping meadowland and in saturating the soil in preparation for a crop.

508. Furrows. — In the furrow system of irrigation the water is led out from the supply ditch on the upper side of the field into small, parallel furrows extending down or across the slope at a considerable grade. This system is used for cultivated field and garden crops, and to a large extent in orchards. The rate of flow of water in the furrows should not exceed one to two feet per second, depending on the nature of the soil. This permits a wide range of grade, from 2 to 10 per cent, where the head of water is only a fraction of a second-foot in each furrow. The flow on a given slope may be regulated by the head of water and is determined by the porosity of the soil. On heavy soil a small head and a steep grade may be employed; on sandy soil, which washes easily, a low grade and a large head of water is used. The length of furrows that may be employed depends on the nature of the soil and the head of water available. The water is distrib-

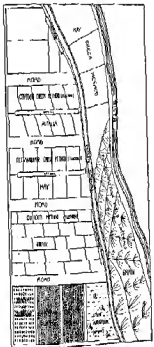

Fig. 78.—Plan of irrigated farm showing the methods of irrigating different crops and the arrangement of the irrigation works for applying the water under the different conditions.

uted from the furrows by percolation and by capillary movement. Percolation causes the accumulation of water under the upper end of the furrows; capillary movement distributes the water laterally as well as downward,

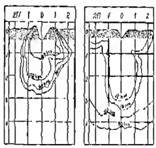

FIG. 79.—Diagram showing the relative rate of movement of water from irrigation furrows into clay loam (left), and sandy loam (right), after different periods of time.

and its rate determines the distance between the furrows. The downward[1] movement is much more rapid than the lateral movement, and both are very irregular, depending on the nature and structure of the soil. Ordinarily the furrows are relatively close together, to give greater uniformity in distribution. In corn, potatoes, berries, garden vegetables, and crops of similar character, a furrow is placed in each row, or at least in every other row as is

[1] Widtsoe, J. A., and McLaughlin, W. W. The Movement of Water in Irrigated Soils. Utah Agr. Exp. Sta., Bul. No. 115. 1912. Also, Loughridge, R. H. Distribution of Water in the Soil in Furrow Irrigation. U. S. D. A., Office Exp. Sta., Bul. No. 203. 1908.

sometimes the case in strawberries, in order to permit harvesting.

In orchard culture two or more furrows are placed between each two rows. Often for young trees a furrow is placed on either side at a distance of about two feet, this distance being increased as the trees increase in size. The furrows are temporary and are usually removed after each application of water, as the establishment of a soil mulch is necessary in order to prevent excessive loss of water by evaporation.

604. Size and form of furrows.— In shape the furrows should be relatively narrow and deep. Water is conserved by this form in three ways: (1) it flows more freely, both in the furrow and into the soil; (2) less surface is exposed to evaporation; and (3) the surface mulch is more easily maintained. (See Fig. 90.) Under arid conditions a deep mulch[1] of six to eight inches is most

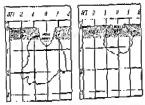

FIG. 90.—Diagram showing the relative advance of water into the soil from a deep (left) and a shallow (right) irrigation furrow. Note the relative extent of surface soil wet in the two cases. A deep mulch and deep irrigation furrows aid in the conservation of moisture.

[1] Fortier, S. Evaporation Losses in Irrigation and Water Requirements of Crops. U. S. D. A., Office Exp. Sta., Bul. No. 177. 1907.

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efficient, and the bottom of the furrow should extend well below its base. This will allow the water to diffuse laterally rapidly, and the deep dry mulch reduces the extent to which the surface becomes moist, thereby conserving moisture and reducing the accumulation of alkali at the surface.

The application of water to the soil in irrigation must be guided by the principles elucidated in the discussion of the physical properties of the soil, and its relation to moisture and its control.

606. **Units of measurement.** — The measurement of water in irrigation practice involves the use of units of volume and pressure. By the head is understood the volume of water applied in the unit of time. The flow of water in canals is usually stated in units of flow per unit of time, that is, the number of cubic feet per second, called the second-foot. Frequently the term second-foot is applied to the volume of water that would result from a flow of that rate throughout the season. A smaller unit is the miner's inch, a term derived from mining practice, which refers to the quantity of water that will flow out of an orifice one inch square under a constant pressure which varies in different states from a four to an eight inch head above the top of the orifice. Like the second-foot, the flow is frequently rated by the season. The pressure is proportional to the depth, or head. It is commonly stated in pounds per square inch. A column of water ten feet in height exerts a pressure of approximately 4.34 pounds to a square inch.

In the field, water is commonly measured in terms of depth over an acre. An acre-foot is the quantity of water that will cover an acre one foot in depth. An acre-inch is one-twelfth of an acre-foot. These are very convenient

terms because of their definiteness and relation to the common method of stating rainfall. Usually an inch or a foot of water refers to that depth over an acre.

Various mechanisms are employed for measuring[1] water in irrigation practice. The commonest of these are the weir and the flume. (See Fig. 81.) The weir is

FIG. 81.—Plank measuring box and a Cippoletti weir used in determining the flow of irrigation water.

a simple device to give the stream a definite cross section and to aid in the measurement of the depth, and therefore the volume of flow. It is usually a knife-edged notch, of a standard shape calibrated to a grade stake a short distance up stream from which the depth of water and its velocity are rated. The measuring box, frequently termed a module, is a box for measuring the flow of water from an orifice under fixed conditions. The Stabilate module, developed in Italy, is most generally adopted for the purpose. Small streams are divided by a knife-edge

[1] Carpenter, L. G. The Measurement and Division of Water. Colorado Agr. Exp. Sta., Bul. No. 150, 4th ed. 1911.

divercer inserted into the current, which diverts a definite portion of the stream. This is called a divider.

606. Amount of water to apply. — The amount of water to apply to the soil at any one time depends on (1) the nature and condition of the soil, (2) the supply of water, (3) the crop, and (4) the season. In the main, enough water should be applied to capillarily saturate the soil to a depth of one foot and to increase the soil moisture to a depth of three feet. A fairly dry, fine-textured soil will effectively take the largest irrigation. Some crops are more sensitive to water at one period of growth than at another. Potatoes should mature in a rather dry soil. The application of water at a single irrigation should ordinarily be from four to eight inches. In very hot weather it may be reduced to two or three inches. In late fall or early spring, when the soil is unoccupied, the application may be relatively larger provided the soil is dry.

Excessive irrigation is to be avoided. While the total yield increases with increase in the application of water up to the maximum point, the unit production decreases.[1] The following brief table, calculated by Widtsoe from actual yields of wheat, illustrates this point: —

	Thirty Acre-inches of Water spread over				
	1 acre	2 acres	3 acres	4 acres	6 acres
Grain (bushels)	47.51	91.43	130.59	166.16	226.10
Straw (pounds)	4532	8908	10256	13804	17910

[1] Widtsoe, J. A. The Production of Dry Matter with Different Quantities of Irrigation Water. Utah Agr. Exp. Sta., Bul. No. 116. 1912.

Small applications of water are relatively most efficient. Up to the limit where injury results, the more concentrated the soil solution, the larger is the yield of crop.

807. Time to apply water. — The best time to apply water depends to a large extent on the nature and habits of the crop. Ordinarily the soil should be thoroughly moistened at the time of planting, in which case the application will have been made before fitting the ground. For sugar beets and other crops planted in rows, it is permissible to irrigate immediately after seeding. The formation of a crust is to be avoided. After planting, water may be applied at intervals of two or four weeks, or when the soil has reached the stage of dryness at which sluggish capillary movement occurs. The experienced irrigator becomes very proficient in recognizing this condition. For grain and forage crops, the soil should be well moistened when the crop approaches maturity. For alfalfa, irrigation may be either shortly before or just after harvest with good results. For root crops a relatively dry condition of the soil at maturity is preferred. The same is true for trees, and the large application of water late in the growing season is especially to be avoided because the new wood growth is likely to be winter-killed. Irrigation in spring, especially at blossoming time, is to be avoided because it interferes with the setting of fruit. One or two thorough irrigations in a season are usually sufficient for the growth of trees. Small fruits should have plenty of water at the maturity of the crop.

Where water is available in late fall and in winter, it may be applied to the soil and stored there for use during the following season. Investigations at the Utah[1] station

[1] Widtsoe, J. A. The Storage of Winter Precipitation in Soils. Utah Agr. Exp. Sta., Bul. No. 104. 1908.

have shown that moisture may be effectively stored in the soil to a depth of more than eight feet and be readily used by crops the next season. The total amount of water to be applied depends on many things. The following factors affect the duty of water: (1) character of the crop; (2) climate; (3) texture and structure of the soil; (4) depth of the soil; (5) fertility of the soil, including the total amount of soluble material; (6) kind of tillage practiced; (7) thickness of planting; (8) season when the crop grows; (9) frequency and method of applying water; (10) amount and time of applying water. A fertile soil and a large and rapid growth of the crop go with economy of water. Many of the above factors, such as thickness of planting, tillage practice, and manner of using water, determine the loss from the soil that has no direct relation to the crop.

The total amount of water to be applied[1] in irrigation should range from five to twenty inches, with the tendency toward the lower figure. This means a duty of 280 to 75 acres a second-foot for a season of sixty days. From one to four applications of water are usually made. The larger the plant and the deeper the root system, the larger the individual application of water may be, and the fewer the number of applications.

608. Conservation of moisture after irrigation. — The conservation of moisture applied by irrigation should be provided for whenever practicable. Crops planted in rows should be cultivated as soon as the soil is dry enough not to puddle. As suggested above, when the furrow method is employed the furrows should be deep, so that only a small part of the surface soil will be wet. Complete

[1] Widtsoe, J. A. Principles of Irrigation Practice, Chapter XVII. New York. 1914.

with this, a mulch of dry soil from four to eight inches deep should be maintained. This is a protection against too high a temperature in moist soil unprotected by shade, as well as against loss of moisture. The surface of the soil should be kept as nearly level as possible.

Crops that are not planted in rows, such as grain, may be cultivated with a fine-tooth harrow until they reach a height of from several inches to a foot, at which stage evaporation from the soil is largely prevented by the shading of vegetation. If it is to be successful this cultivation must begin as soon as the seedlings appear above the surface, in order that the roots may be forced deep into the soil. Then the top may be much twisted with but little injury to the plant, and that injury appears to be more than counterbalanced by the tillering of the plant. By prompt and thorough tillage following irrigation, very much may be done not only to conserve soil moisture but also to prevent the accumulation of alkali at the surface by evaporation.

609. **Sewage irrigation.** — A phase of the general practice of irrigation is the application of sewage [1] to the land for purposes of crop production. This supplies plant-food as well as water. The food content, however, is relatively small, being about two parts in one thousand, of which one-half is organic and one-half is inorganic material. In European countries sewage irrigation is extensively employed near cities, but in the United States the practice has not been largely followed. The city of Boston has carried out extensive experiments, and the city of Los

[1] Rafter, G. W., and Baker, M. N. Sewage Disposal in the United States. New York. 1894. Also, Rafter, G. W. Sewage Irrigation. U. S. Geol. Survey, Water-Supply and Irrigation Papers, Nos. 3 and 22. 1897 and 1899.

Angeles has a large farm irrigated with sewage water. The same general principles prevail in the use of water as in normal irrigation practice, except that the soil may become clogged and foul from the accumulation of solid material, especially where the idea of disposal overshadows that of efficient use. This practice is used chiefly for the production of hay and forage.

DRY-FARMING

The water supply for irrigation is sufficient for only a small part of the earth's surface which needs such treatment. The remainder of this vast area of land having a deficient rainfall must be utilized, if at all, by the most scrupulous and careful conservation and use of the natural rainfall. The growth of crops without irrigation under such conditions is termed dry-farming.[1] It is merely an intensified form of the methods which are recognized as good practice to conserve moisture in more humid regions.

Dry-farming is based on the principle that the production of dry matter in crops requires only a small part of the water which may be used in one way or another in its growth, and that a large part of that water is lost by sur-

[1] Widtsoe, J. A. Dry Farming. New York. 1910. (Appendix includes a large list of references on dry land farming.)

MacDonald, Wm. Dry Farming. New York. 1910.

Campbell, H. W. Soil Culture Manual. Lincoln, Nebraska. 1907.

Chilcott, E. C. Dry Farming in the Great Plains Area. U. S. D. A., Yearbook, pp. 451–468. 1907.

Briggs, L. J., and Shantz, H. L. The Water Requirement of Plants. Investigations in the Great Plains in 1910 and 1911. U. S. D. A., Bur. Plant Ind., Bul. 284. 1913. Also, the Water Requirements of Plants. A review of literature. U. S. D. A., Bur. Plant Ind., Bul. 285. 1913.

face flow, by seepage, and especially by evaporation, without performing any useful service to the plant.

610. Practices in dry-farming. — The practice of dry-farming may be divided into three groups: (1) the maintenance of such a condition of the soil at all seasons of the year as will insure the complete absorption of the rain and snow-fall, (2) the conservation of the stored moisture by appropriate methods of tillage, (3) the selection of drought-resistant crops and of rotations adapted to the small use of water.

611. Storage of water in the soil. — In different regions the rainfall occurs at different seasons. A loose, open condition of the surface soil should be maintained during that period. This may require deep plowing, and if the subsoil is compact it may include subsoiling. Where the precipitation comes as snow, the surface should be rough so as to prevent drifting, in order that the resulting water may be uniformly absorbed by the soil. Fall plowing is an important factor where much of the precipitation comes in winter and the soil is compact. Another reason for the maintenance of a ridged surface is to reduce erosion by the high winds which frequently occur in winter in dry-farming regions and which cause the serious removal of the soil. The roughened surface impedes the wind movement, and the moist soil at the crest of the ridges resists erosion.

612. Conservation of moisture. — The conservation of the moisture in the soil involves two things — an increase in the capillary capacity of the soil, and the prevention of evaporation. Where the rainfall is low, the deep subsoil is usually very dry. The rainfall penetrates to a limited distance from the surface. Having loosened the subsoil so that the rainfall is absorbed, the next step is to compact

the substratum as much as possible by tillage in order to increase its capillary capacity. The need of this treatment, of course, depends on the nature of the soil, and is not always the most favorable. It is undesirable that this packing should extend to the surface. Following the plow, the land is frequently worked down with a subsurface packer, an implement of considerable weight, made up of openwork rims that press the soil together and at the same time leave a mulch on the surface. By acting on the lower part of the furrow instead of on the surface, the packer brings it into closer contact with the subsoil and thereby establishes better capillary connection.

After thorough packing of the main part of the furrow, a dust mulch is maintained on the surface. This should be of medium depth in the season when rains are likely to occur, and of somewhat greater depth during the dry period. Two or three inches is usually a sufficient depth.

Various applications of the principle of mulching may be employed. Land may be disked before plowing in fall or spring, to hold moisture until the plowing can be done. As soon as a crop is removed, the land should be plowed or tilled and worked down to a good mulched surface. Land should not be allowed to stand unworked for any considerable time after harvest. All weed crops should be kept thoroughly mulched. Much may be done to conserve water in grain and hayfields by tillage. The same principles apply to the practices that are used on irrigated land. Special revolving toothed implements have been devised to loosen up the surface soil under such conditions.

613. **Alternate cropping.** — Where the rainfall is too light in a single season to permit the production of a profit-

able crop, it is sometimes the practice to collect and store the rainfall of two seasons in the soil. This is the system of alternate-year cropping. In the intervening year the soil is carefully fallowed and mulched, to hold the stored moisture. That such long-time storage of available moisture is possible has been clearly demonstrated[1] under dry-farming conditions, and also in the study of irrigation problems. An arid or a semiarid climate is especially favorable for the formation and maintenance of an efficient dust mulch, and the occurrence of dry earth in the lower subsoil permits moisture to be stored and retained in large quantities within reach of the roots of crops. It is believed by some persons that the practice of fallowing in alternate years is very destructive of organic matter in the soil, and that it may be better to grow a green-manure crop in that period to be turned under. It is questionable whether the loss of water may not be a serious objection to this.

614. Drought-resistant crops. — For growth under dry-farming conditions, crops are preferred which have a low moisture requirement, which are not seriously affected by severe drying, and which have a fairly deep root system. The sorghums come in the first class and also fulfill the second requirement. Corn is fairly satisfactory. Wheat, barley, and alfalfa are favorite dry-farm crops. Drought-resistant varieties of these crops are being sought. A rotation is desirable which exposes the soil as little as possible to evaporation, and permits continuous mulching with the minimum of plowing.

[1] Atkinson, A., Buckman, H. O., and Gieseker, L. F. Dry Farm Moisture Studies. Montana Agr. Exp. Sta., Bul. 92. 1901. Also Burr, W. W. Storing Moisture in the Soil. Nebraska Agr. Exp. Sta., Bul. No. 114. 1910.

614. Soils associated with dry-farming. — Dry-farming is often closely associated with irrigation, being practiced on the heavier soils where the water-storage capacity is large and where the practice of irrigation is most difficult. Successful dry-farming requires an annual rainfall of at least fifteen inches, and twenty inches is much safer as a basis for the practice. A general principle to be observed in dry-farming is that the shorter the soil moisture supply, the lighter should be the rate of seeding. Wheat, for example, may be seeded at the rate of only twenty pounds

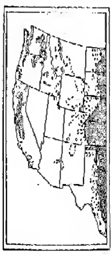

FIG. 82. – Areas of western United States where dry-land farming is or may be practiced.

to the acre. The crop will stool out strongly and adjust itself to the moisture supply. Under dry-land and irrigation farming, crops as a rule root much deeper than in humid soils.

616. **Extent of dry-farming.** — In the United States many thousands of acres in the Great Plains region, in the semiarid northwestern valleys, and in the Pacific Coast States, are now being cropped under systems of dry-farming (see Fig. 82). Further, the practice is beginning to be followed somewhat more definitely in all parts of the world where similar conditions prevail. The large open areas of land and the dry climate in such regions have encouraged the employment of larger power equipment in planting and harvesting the crops, especially wheat. In parts of California machines are used which cut, thresh, and sack the grain in one operation.

The study of the principles on which dry-farming is based, together with the extension of their practice, may be expected to bring large areas of land, now substantially worthless, to a measurable degree of productiveness. The tendency in the practice of both dry-farming and irrigation is toward the more efficient use of water for purposes of crop production, and to approach the actual requirements of the plant in the utilization of water. In both cases the fundamental principles in the storage, conservation, and use of water by plants must be observed, as well as care regarding the application of these principles according to the soil, the crop, and the nature of the water supply.

CHAPTER XXXI

THE SOIL SURVEY

THE function of the soil survey is to investigate the nature and occurrence of soils in the field. The soils are classified into areas having approximately the same crop relations and tillage properties. The location of the areas of each kind of soil is represented on charts or maps, and their character and chief economic and agricultural relations are described in printed reports.

817. **The classification**[1] **of soils by survey.** — The occurrence of differences in the tillage and manurial re-

[1] Klassifikation, Nomenklatur, und Kartierung der Bodenarten.

Verhandlungen der zweiten Internationalen Agrogeologenkonferenz. (Proceedings of the Second International Agro-geological Conference, Stockholm, Chapter V, pp. 233–298. (Seven papers.) 1911.

Report on Soil Classification. Proc. Amer. Soc. Agron., Vol. 6, No. 6, pp. 284–298. 1914.

Fippin, E. O. The Practical Classification of Soils. Proc. Amer. Soc. Agron., Vol. 3, pp. 76–89. 1911.

Marbut, C. F. Soils of the United States. U. S. D. A., Bur. Soils, Bul. 96, pp. 7–16. 1913.

Coffey, G. N. A Study of the Soils of the United States. U. S. D. A., Bur. Soils, Bul. 85, p. 114. 1912.

Hall, A. D., and Russell, E. J. Soil Surveys and Soil Analysis. Jour. Agr. Sci., Vol. 4, Part 2. 1911.

Tulaikov, N. The Genetic Classification of Soils. Jour. Agr. Sci., Vol. 3, pp. 80–85. 1909.

Stevenson, W. H., Christie, G. I., and Willcox, O. W. The

quirements of soils, their crop relations, and their agricultural value make necessary the determination of the properties of the soil that are chiefly responsible for those differences, and their arrangement into an orderly scheme of classification. The aim is to divide the land into areas of approximately the same general character. This volume is largely an exposition of those properties of soils that make differences in their crop relations and management. It is evident that differences are numerous and varied, and that some have greater significance than others.

Soils may be classified from many different points of view. The basis may be purely geological, purely physical, or almost entirely chemical. Any one of these alone is likely to be inadequate for the purposes of the agriculturist. The viewpoint of the agricultural soil survey should be such as to secure unity in the crop relations of each distinct area of soil recognized.

The system of classification in use must employ as a basis some combination of the groups of properties enumerated above. The combination selected has differed in different parts of the world, depending on the training

Principal Soil Areas of Iowa. Iowa Agr. Exp. Sta., Bul. 82. 1905.

Mooers, C. A. The Soils of Tennessee. Tennessee Agr. Exp. Sta., Bul. 78. 1906.

Shannon, C. W. The Indiana Soil Survey. Dept. Geol. and Natural Resources, 32d Ann. Rept., pp. 17-47. 1907.

Hopkins, C. G., and Pettit, J. H. The Fertility of Illinois Soils. Illinois Agr. Exp. Sta., Bul. 123. 1908.

Hall, A. D., and Russell, E. J. Report on the Agriculture and Soils of Kent, Surrey, and Sussex. Dept. Bd. Agr. and Fisheries. London. 1911.

Kümmel, H. B. Soil Surveys as Related to Geology. N. J. Bd. Agr., 36th Ann. Rept., pp. 163-169. 1908.

of the person by whom the survey was proposed, and the kinds of soils and crops with which he dealt. Some persons have used the vegetation,[1] especially the native vegetation, as a means of classifying soils. Where this is present it is an excellent means of identifying differences, and pioneers as well as others have always made use of the vegetation growing on a soil to detect variation in its cropping capacities. Unfortunately the vegetation, whether native or introduced, being a result of natural causes, affords information regarding the properties of a soil only when the correlation has been worked out. Further, the native vegetation is now seldom present in well-settled areas, so that it is inadequate as a general means of classification, though very useful for some purposes of comparison.

618. **Factors employed in classification.** — In classifying soils, four primary and two secondary factors are employed. The former group deals entirely with the soil itself; the latter group deals with the climate or the situation in which the soil is placed. The situation exerts an influence on the crop value and on the properties of the soil. The factors, beginning with those of the smallest range of occurrence, are as follows: (1) texture, (2) special properties, chiefly chemical, (3) kind of material from which the soil was formed, (4) agency of formation, (5) humidity and precipitation, and (6) normal and mean temperature.

The soil type is the unit of classification, and may be defined as an area of soil that is essentially alike in all the above characters.

[1] Hilgard, E. W. Soils, Chapters XXIV, XXV, and XXVI. New York. 1906.

Outline of the Factors Used in the Classification of Soils

Number	Name	Factor	Partial List of Subdivisions	Example of Application to Miami Clay Loam
I.	Region	— Temperature	1 Frigid 2 Temperate 3 Subtropical 4 Tropical	Temperate
II.	Section	— Precipitation	1 Humid 2 Semiarid 3 Arid	Humid
III.	Province	— Agency of Formation	1. Weathering 2. Biology 3. Water { a. Streams, b. Lakes, c. Ocean } 4. Atmosphere 5. Glaciation 6. Gravity	Glaciation
IV.	Group	— Kinds of Material	1. Acid crystalline rock 2. Basic crystalline rock 3. Shales and sandstone 4. Limestone and marl 5. Organic matter	Shale, sandstone, limestone, and some crystalline rock
V.	Series	— Specific Properties	1. Color 2. Natural drainage 3. Content and condition of organic matter 4. Content of lime carbonate 5. Content of plant-food 6. Arrangement of soil in section	Yellow to brown Medium Medium to low Medium Normal
VI.	Class	— Texture	1 Size of particles	Clay loam

619. Texture — the soil class. Of all the properties of the soil, the one which is most apparent and which exerts the most direct influence on the plant is the texture, or fineness of division, of the soil particles. Is it a clay, a silt, a sand, a gravel, or some combination of these? Is it stony, or is it free from stone? The texture is the first property made use of in classifying soil. This division based on texture is called the soil class. It is a purely physical division, and does not recognize any chemical or other differences in the soil except as such differences may occur between coarse and fine materials.

620. Special properties — the soil series. — Soils of different texture may be alike in other properties. They may be all red, all black, or all yellow. They may be well drained or poorly drained. Such a group of soils of different texture but alike in all other properties constitutes a soil series. The properties by which the soil series is recognized are (1) color, which is predominant in the separation, (2) content of organic matter, (3) natural drainage, (4) content of lime carbonate, (5) ultimate chemical composition, and (6) arrangement of the soil in the section. Any one or a combination of these properties may identify an area of soils. Such an area would constitute a soil series. These properties permit the recognition of chemical differences quite as much as physical differences of the soil in mass.

If it were possible clearly to identify all the properties that may be recognized in the series and class divisions, there would be no need of employing other factors in the classification. Such a clear identification, however, is only partially possible, and is further limited by the conditions under which the soil survey must be carried out in the field. Many of these properties are of such

so intimate nature that they cannot be recognized by inspection. However, they are correlated with the origin and mode of formation of the soil, and therefore the use of these factors in the classification is justified as an aid to rapid and accurate field identification.

621. Source of material — the soil group. — The soils of a region may be similar in many properties because they have been derived from the same kind of rock. They may be similar also because they have been derived from the same mixture of different rock materials. As a result of the many kinds of rock and the different proportions in which they may be mingled, many groups of soil series may be recognized. Some of the commoner groups of rocks identified with these differences are acid and basic crystalline rocks, shales, sandstone, and limestone.

622. Agency of formation — the soil province. — The way in which a rock formation has been broken down and the residue brought to its new resting place affects both the chemical and the physical nature of the resultant soil. The six groups of forces that have been predominant in the formation of soils are: (1) weathering, or the decay and disintegration of rocks in place, forming a residual soil; (2) biological processes, which form organic matter and give rise to cumulose soils; (3) water in streams, lakes, and oceans, which reduces, transports, and sorts soil-forming materials, and which imparts to its deposits a distinctly stratified arrangement; (4) atmosphere, especially as moving wind, which exerts an abrasive and sorting action similar to that of water but with a very much smaller range in the texture of the strata formed, and with a type of stratification also distinct from that formed by water; (5) glaciation, or the action of continental masses of ice, the deposits from which are

exceedingly heterogeneous in nature and are without sorting or stratification except as the action of wind and water may have combined with the action of the ice; (6) gravity, or the slow creep of material on slopes, which is a minor agency of soil formation (see Chapter II).

623. Climate. Soils owe their origin to the operation of one or more of the forces named above. Usually some one of these agencies is predominant and gives specific character to the soil. The elements of climate have been used in the practical classification of soils to only a small degree, since the inherent properties of the material in these divisions are usually distinct enough to make separation easy. The excessive accumulation of the soluble salts known as alkali is associated with a low rainfall, and other chemical and physical properties are correlated with aridity. Three main divisions in humidity and precipitation may readily be made, namely, (1) humid, (2) semiarid, (3) arid. The exact precipitation limits of these divisions depend on the temperature relations and the time and manner of occurrence of the precipitation.

In a world system of soil classification the temperature relations of the soil would be recognized, but this division is seldom important in any single country.

624. The practical classification of soils in the United States. — As practiced in the United States, the classification of soils[1] has disregarded the climatic factor and has usually combined the kind of rock and the agencies of formation as a single basis of separation of soils, designating the division resulting therefrom as a soil province. In some areas one element of formation is dominant and

[1] Marbut, C. F., Bennett, H. H., Lapham, J. E., and Lapham, M. H. Soils of the United States. U. S. D. A., Bur. Soils, Bul. 96, p. 201. 1913.

in other areas another element is dominant. To this extent the classification deviates from the ideal system outlined above.

625. **The soil type and series. How characterized and named.** — The two predominant divisions of soil are the soil type and the soil series. The soil type is the unit of field study and classification, and corresponds to a species of plant or animal in biological classification. It includes all those areas of soil that are essentially alike in all properties — texture, color, chemical nature, structural properties, source of material, and mode of formation. In other words, soils of the same type are as nearly alike as field identification will admit. The soil series is a group of types differing only in the texture of the different members. This may be said to correspond to the genera in biological classification.

A name is given to each series of soil for purposes of easy identification, and to this name the class designation is added, thereby fixing the identity of the type. For example, the Miami series includes certain light-colored, timbered, glacial soils of the East Central States. The Hagerstown series includes certain light brown to reddish residual limestone soils, found in the blue-grass region of Kentucky and adjacent states. The Norfolk series includes brown yellow, marine-deposited soils of the coastal plain of the Atlantic and Gulf regions. Clay loam would refer to a particular texture of any of these series, as the Miami clay loam, for example, thus completing the type name of a soil, which is made up of the series name and the class designation.

The common practice is to select for the series designation some geographical name in the region where the soil is first identified or is best developed. The word

Miami is taken from the Miami River in southwestern Ohio, where the Miami series was first recognized.

This system of a proper generic name and a descriptive class name is most widely used in the United States to identify the soil type. It gives a specific identity of the soil in its situation and in all its properties.

Hopkins[1] has proposed and used the Dewey Library System of numerical naming of soils, by which each property is given a fixed series of numbers and the identification number is obtained by combining the numbers that represent its properties. Whole numbers are assigned to important and definite soil types, and decimals are used for related types possessing some distinct variations. For example, 451.2 represents a glacial soil made up of brown loam on silt. While the numbering system of designation is admirable in many ways, it does not lend itself to the same practical use that is possible with a proper descriptive name.

698. The equipment for survey work. — The most important part of the equipment for soil survey work is the field man. He should be a keen and careful observer, and he should have had broad training for his work. He should be acquainted with the technic of soils in the laboratory and in the field. He should be familiar with the chief physical and chemical processes and material involved in soil formation. He should have an understanding of that phase of geology known as physiography. On the agricultural side, he should be acquainted with plants and the methods of growing the more important crops. He should know tillage practice, and should be

[1] Hopkins, C. G., and Pettit, J. H. The Fertility of Illinois Soils. Illinois Agr. Exp. Sta., Bul. 123, p. 252. 1908.

able to distinguish between the properties of the soil that are native and permanent and those that may be induced by the method of handling. There is very little knowledge of natural phenomena that will not be found useful to the field man in classifying soils, because he uses all sorts of observations in making and checking his divisions on soils. In brief, he should have a good training in the fundamental technic of geology, chemistry, and agriculture.

In the way of physical equipment the field man should have a good map of the region, on a scale of one inch to a mile or larger. The field work should be done on at least as large a scale as the finished map, as this increases the degree of accuracy. The map should show the roads, streams, and towns of the region, and in addition the topography, location of houses, and other natural and cultural features which are useful in placing boundaries of soil. Where a satisfactory map is not available the field man must make such a map[1] during the progress of the soil survey. For this purpose a Gannett plane table, a sight alidade, and some method of measuring distance — preferably an odometer, such as is used for counting the revolutions of a buggy wheel — are necessary. Cloth-back drawing paper is generally used.

Where a suitable base map is already available, a set of pencils of different colors for representing each type of soil on the map as it is recognized is essential. A horse and buggy is the usual method of conveyance. For examining the soil a soil auger is used (see Fig. 83). This consists of a one-and-one-half-inch wood auger attached to a half-inch pipe rod with a T handle, making a total length

[1] Instructions to Field Parties. U. S. D. A., Bur. Soils. 1914.

of about thirty-eight inches. By the use of additional sections the length may be increased. The end of the auger may be modified by cutting off the screw and the cutting jaws, to better adapt it to the work in soil. Generally a bottle of muriatic acid for detecting carbonates, and strips of sensitive litmus paper of red and blue for testing for soil acidity, are useful adjuncts to the equipment. In arid regions where important quantities of alkali are met with, the field man should be supplied with a modified Wheatstone bridge and chemical equipment necessary for the detection and measurement of the important salt constituents[1] A geologist's hammer for examining soil and rock should be added, together with such other minor equipment as may increase the convenience and efficiency of the work. A substantial field book should be provided, for notes on the character of soil types and other observations and data, and for records of borings and samples. The notes should be carefully classified. Muslin bags of about one quart capacity should be used for collecting and shipping the samples to the laboratory for mechanical analysis. Where the natural field structure and

FIG. 83.—Auger used in the examination of soils: (A), handle; (B), joint; (C), worm with modified cutting edge.

[1] Davis, R. O. E., and Bryan, H. The Electrical Bridge for the Determination of Soluble Salts in Soils. U. S. D. A., Bur. Soils, Bul. 61. 1910.

moisture conditions of the sample are to be preserved, wide-mouth, sealed-top, metal or glass containers should be used. Aluminum cans are usually most suitable, as they are not corroded by the sample.

627. Procedure in the field. The area for survey having been selected, the field party — which usually consists of two men, a chief and an assistant — proceeds to examine the soils of the district. Headquarters are temporarily established in a convenient village or country residence, and excursions are made into the adjacent territory. The routes are laid out carefully and systematically with the purpose of examining the soils of the entire area. The party proceeds along the highway, with frequent stops and side excursions into the field, examining the soil to a depth of three or more feet with the auger. In humid regions the basis of the soil classification is a section of soil three feet deep. In arid regions, where alkali is prevalent, a six-foot section is usually the basis of classification, and occasionally much deeper examinations are made for studying the position of the water table. The soil is examined especially with reference to its texture, structure, color, drainage, content of organic matter, depth of different strata, and special chemical properties such as lime and alkali. The natural vegetation is observed, and note is taken of the type and growth of crops as well as the extent and species of forest trees.

Borings and other observations are made from point to point as the appearance of the soil, the topography, the conformation of the country, and the character of the vegetation may suggest. The frequency and position of observations are determined entirely by the judgment of the field man. They may be made every few rods or at

much wider intervals. In getting acquainted with new types, more borings and detailed observations are necessary than after the soil properties have become familiar and can be more readily identified. Where the soil is highly variable, much more frequent observations are necessary than where it is more uniform. As the survey proceeds the field man progresses from point to point, along the highway and in the field, on foot or by conveyance as may be more convenient, extending his observations about half the distance to the next highway in order that all the territory may be covered most conveniently. Usually the trip is arranged in a circuit. All areas of soil essentially alike in their properties and plant relations are recognized as of the same soil type, and their position on the map is represented by one of the colors. As the observations proceed, a change in the character of the soil may occur. When this change becomes of such character and importance as to cause difference in agricultural relations and to be recognizable under the plan of classification outlined above, a new type is recognized. The boundary line between the two types must be carefully traced out by observation and by borings. As the work proceeds other types of soil may be recognized and the boundaries are determined and represented on the map, each type being indicated by a particular color or symbol. A large number of types of soil may be recognized in each area surveyed. The character and relationships of these must be studied carefully in order to decide how they may be grouped in series and larger units.

In practice it is usually better for the field party to first make general observations over the area, in order to recognize the main divisions of the soil that may later require subdivision into types. To this end all available

facts, particularly concerning the geology of the region, should be familiar to the survey man before active field work is begun. It is easier and results in a greater degree of accuracy to first recognize the large divisions of an area of soil, and later work out the types, than to be concerned from the very beginning entirely with these detrimental subdivisions.

During the progress of the field observation the relationship of each type of soil to natural and cultivated plants should be studied, and the tillage properties of the soil noted. The farmers also may be interviewed concerning their soils, as to tillage properties, crop relations, and response to methods of improvement. In short, all available data concerning the character of the soils of the region should be sought.

Records are made in the field notebook descriptive of the average character of each type of soil. The description of typical borings may be recorded and their location noted on the map. Preliminary samples may be taken and sent to the central laboratory for physical or chemical examination, to check the judgment of the field man.

628. Collection of soil samples. Samples of soil for laboratory examination should be taken only after the field man is thoroughly familiar with each type of soil and can select a location that accurately represents the average material of the type. Attention should be given to the slope, drainage, abnormal modifications, and manurial treatment of the soil at that point. Therefore, in survey work samples are collected only in the latter part of the season. One or more samples of each important type of soil are taken. The material, to the amount of a quart, is preserved in cloth bags. Usually each sample is divided into two parts, one representing

the soil and the other the subsoil. If there is a marked change in appearance or texture in the subsoil, other divisions of the sample may be made. Usually a composite of a number of borings over an area of several square rods, or even of several acres, may be necessary in order to secure an accurate sample and to obtain enough material. A composite of several representative borings made over a considerable area gives a more nearly accurate sample than is possible in a single boring. The possibility of local variations is very great, and their effect is reduced when composite sampling is done.

Each bag should bear a tag which is given a number and on which is placed the name of the type, the location of the sample in the section, and a brief description of the material. The same data are recorded in the field notebook, which is finally preserved as a part of the permanent office record of the survey. The description in the notebook may be amplified more than is possible on the tag. The location where each sample was taken should be accurately marked on the field map by a number corresponding to the number of the sample. Usually each sample is given a number, and the parts are indicated by a letter, proceeding from the surface downward. Where the material is very wet and likely to become lumpy when dry, it may be dried in a thin layer before being finally bagged for shipping or preservation. Care should be bestowed on every part of the operation of collection, describing, numbering, tagging, tying, and shipping, in order to insure accuracy and permanency of the record.

The soil auger is generally used in taking the sample and in examining the soil section. The worm of the auger is bored into the soil until it is filled. It is then withdrawn and the soil is removed. The soil may be

collected on one or more squares of oilcloth, or it may be placed directly in the appropriate bags. The worm of the auger having been cleaned, it is inserted into the same hole and advanced until it is again full, when it is withdrawn and cleaned as before. This operation is repeated until the desired depth is reached. Where the soil is a very heavy clay, it may be advisable to only partially fill the worm with soil. Where the soil is very dry and pulverizes to a dust, it may slip off the worm, in which case water may be added to make it adhere. The upper part of the hole should be cleaned, and it may be slightly enlarged so as to prevent contamination with the material from the lower part of the section. Where there is rubbish on the surface, this should be removed previous to beginning the collection of the sample.

In very stony soil the auger is not suited to taking a sample, either for examination or for record. In such soil a shovel may be used, or the sample may be taken in a road or some other cut by means of a geologist's hammer.

The face of the section should be removed to a depth of several inches, in order to eliminate weathered or contaminated material which may not be typical of the soil section. Usually a difference in color and physical properties of the soil indicates a modification of the typical material.

690. The accuracy and detail of the soil survey. — The accuracy and detail of the soil survey depend on many things. Assuming an adequate preparation on the part of the field man, there are limitations in accuracy imposed by the scale on which the map is made and the nature of the soil. The smaller the scale of the map used in the field, the less is the detail that may be represented. The commonest scale employed is one inch to a mile. Some

states use a larger scale, and in reconnoissance surveys a smaller scale is used. While a large scale increases the detail that may be represented, it also multiplies the difficulties of making an accurate classification because it increases the number of properties to be observed.

The nature and occurrence of soils in the field involves more variations than can be shown on the map. The boundaries of soil types grade into one another, and it may not be possible to mark the division within several rods. Sometimes even a wider range occurs. The accuracy with which the boundary may be determined and drawn depends very much on the way in which the two adjacent soils have been formed. If they are very different, the boundary may be very distinct. Some types of soil are characterized by local variations in sections, or from point to point, which are on too small a scale to be recognized as a type. Variations may be induced in a type due to differences in topography, drainage, or cultivation. Where the properties do not bring about an important change in the crop relations of the soil, they may be ignored. Differences due to cultivation are generally disregarded. The soil survey is made to cover a period of years, and only permanent differences should be considered.

Variations in the soil must be considered in relation to the scale of the map. On a scale of one inch to a mile the minimum area that can be shown is about ten acres. Occasionally, where the difference in type constitutes a striking contrast, the small area may be somewhat exaggerated in size. An area of muck soil having high value for the production of truck crops might be such an exception.

630. The soil survey report.—The soil survey report consists of two parts, the printed report and the map showing the distribution of the soil types. The printed report accompanying the soil map should be a brief but comprehensive summary of the observations of the field party in the areas surveyed. It should cover six types of information: (1) location and boundaries of the area; (2) general physical features; (3) climate; (4) agricultural history and development; (5) description of the soils; (6) suggestions for improvement in the management of the soil that may have been determined by the survey.

The description should point out the salient topographic forms, the range in elevation, the nature and development of the drainage, the transportation facilities, and the distribution of population and of farm areas. The discussion of climate should note the monthly mean temperature and amount of precipitation; the character of the extreme ranges in these; the direction of prevailing winds; and the occurrence of any special features, such as untimely frosts, sleet and hail and windstorms, and the nature of local variations in climate that may be due to the proximity of bodies of water or topographic features. The agricultural history should note the source and character of the agricultural population, the chief products and any changes that have occurred in their production, and the present status of the area.

The description of the soils should be in two parts. First, the grouping of the types into series and larger divisions, with the geological and topographic relations of these groups and a clear statement of the characteristic properties of each group. Any important characteristics that are common to two or more types or series, such

as a deficiency in humus, lime, or drainage, should be pointed out. Secondly, a detailed description of each type following a uniform outline of properties, including color, texture, depth, structural peculiarities, and mineralogical and chemical features. Following this, attention should be drawn to the location and extent of the type in the area, and to its mode of origin, drainage conditions, and economic relations, including the crop rotation and extent of development.

In making suggestions for the treatment of the soils a clear distinction should be drawn between methods of soil management and improvement, and questions of farm organization and management. The data collected by the soil survey man will usually lead him to confine his suggestions to the former group.

631. The soil map (Fig. 84). — The soil map is designed primarily to show the geographic position and extent of each type of soil. Therefore an accurate base map, showing important natural and cultural features as noted above, is essential. The scale of the map must be adapted to the amount of detail to be shown. The commonest scale in use in the United States is one inch to a mile. In reconnaissance surveys a scale of one inch to six miles is usually employed. The map is printed in colors or in symbols representing the different types of soil. Symbols may be added to the color to indicate further variation, such as the presence of much stone, occurrence of ledge rock, or a swampy condition. On the right-hand border of the map a legend to the colors or symbols is given, and they may be arranged in accordance with the scheme of classifying the soils to show their relationship. On the left-hand border, the character of the profile of each type of soil is indicated by a series of legends.

Fig. 86.—Part of the Madison County, N. Y., soil map showing the topography and the relation of the various soil types to one another.

632. **The extent of soil surveys in the United States.** — The detailed survey and mapping of soils by the Bureau of Soils of the United States Department of Agriculture, according to the scheme outlined above, has been in progress since 1899. On January 1, 1925, about 330,000 square miles had been covered by detailed surveys and 925,000 square miles had been covered by reconnoissance surveys. In addition, several miscellaneous surveys have been made in outlying provinces such as Porto Rico, Panama, Philippine Islands, and Alaska. The total number of soil types and series recognized is approximately 2000 and 600, respectively.

633. **Surveys by state institutions.** — Several states are engaged in soil survey work, either independently or in coöperation with the United States Bureau of Soils. The states that have undertaken this work independently have carried it out in the same general manner as in the Federal survey. Some of the states that are working independently have confined their investigations to reconnoissance surveys on a large scale. Tennessee has published a general report, with a map, on the soil areas of the state, with special reference to their geological relations. Account is also taken of the texture, chemical composition, and other properties. Iowa, Missouri, and Illinois and Ohio[1] have published similar general reports showing soil areas based chiefly on origin. Illinois, Indiana, and New Jersey have also published detailed reports on particular areas. In their work the principles of classification laid down above have been followed in a general way, but with emphasis on certain selected properties.

[1] Coffey, G. N., and Rice, T. D. Reconnoissance Soil Survey of Ohio. U. S. D. A., Bur. Soils, Field Op. p. 139. 1913.

Illinois has given special prominence to color, and, in addition to the general description of the soil types, includes data derived from chemical analyses to show the store of plant-food in the surface layers. The Indiana and Missouri surveys have combined a purely geological scheme of classification on the basis of origin, with certain properties of practical importance, such as texture, color, and content of humus, but without observing a systematic order. The New Jersey survey includes rather full data on the chemical composition of the soil types, in addition to the usual discussion of their properties and relationships.

634. Surveys in other countries. — Several countries have undertaken some type of soil or agrogeological survey. These surveys, which have been undertaken in Germany, France, Italy, Russia, Great Britain, and Japan, have aimed at a broad practical classification of soils based on their agricultural values and tillage properties. Several thousand square miles have been covered by the surveys in each of these countries. Colored charts are published to accompany the descriptive reports. In these surveys the classification is largely genetic, in combination with a consideration of the more evident physical and chemical properties, which are recognized and grouped in the field in much the same manner as in the American surveys. The details, of course, are considerably different in the reports of the different countries. In Germany the maps are geological-agronomic in character; that is, prominence is given to both the geological and the crop relations of the soils. Their physical and chemical properties are pointed out and are used in the classification. Similar methods are followed in France and Japan.

In England the areas of soil are determined, first, by means of their texture; secondly, by means of their con-

tent of humus and lime carbonate, with which color and drainage are associated; and thirdly, by means of the geological formation and mode of origin. Fairly complete mechanical and chemical analyses of representative samples of the important types are included, and the relation of the soils to crops and farm practice is discussed at some length. The grouping of the types into series, groups, provinces, and the like, is not so distinct as in the American surveys. That the fundamental importance of the larger factors in classification are recognized is shown in the discussion of the relation of precipitation and temperature to the properties and agricultural uses of the soil, in which the controlling influence of these over large areas is pointed out.

536. Uses of the soil survey. — The soil survey is useful in many ways, but it is not a final investigation. It is to be regarded rather as a means of determining the status of the soil and related conditions in the field. These may throw light on many farm practices and lead to their improvement. More frequently the soil survey points to lines of further investigation that should be carried out.

The uses of the soil survey may be conveniently divided into two groups — its use to the individual, and its use to the state. For the individual, the soil survey (1) points out the character and location of the several types of soil on his farm which may be correlated with particular crops and farm practices; (2) shows him the relationship of soils over wide areas, which may form a basis for the adoption of new crops or new methods of soil management; (3) provides a reliable central source of information concerning soil conditions; (4) standardizes methods of description and representation of soils; (5) reveals in

many cases important problems of soil improvement that need attention; (6) affords a guide in the exchange of real estate and in the selection of land for particular purpose. For the state the soil survey (1) shows its soil resources, (2) by the collection of this data at a central point, affords the basis for the correlation of all other types of information, the character of which is affected by the soil relations; (3) shows in many cases the occurrence and importance of large questions of soil improvement, and may point out the need for further investigations; (4) gives a basis on which much of the results of experiments, investigations, and observations on soil improvements, crop growth, and in many cases farm management, should be applied; (5) is a means of communication and mutual understanding between the state institutions concerned with agricultural information and the individual farmer; (6) by affording a basis of facts, promotes sound commercial, social, and governmental development.

The soil survey is essentially an inventory of the resources in land and closely allied interests. It helps the farmer to understand the situation of his farm and its relations to other farms. It helps the state to get acquainted with its domain, and promotes a better sense of mutual understanding and helpfulness. The soil survey in some form is an essential step in sound community building, for the success of most interests — commercial, social, and institutional — rests ultimately, to a large extent, on the character and value of the soil.

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Professor of Floriculture in the New York State College of Agriculture at Cornell University

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